NT

NASA TECHNICAL MEMORANDUM

DOE/NASA TM-82455

(NASA-TM-82455) LONGWALL GUIDANCE AND CONTROL DEVELOPMENT Final Report, 1974 - 1982 (NASA) 118 p HC A06/MF A01 CSCL 08I

N82-19637

Unclas
G3/43 09222

LONGWALL SHEARER GUIDANCE AND CONTROL - FINAL REPORT

By Special Projects Office

January 31, 1982

Prepared for the U. S. Department of Energy

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. DOE/NASA TM-82455	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Longwall Guidance and Control Development: Final Report for the Department of Energy

5. REPORT DATE
January 31,1982

6. PERFORMING ORGANIZATION CODE
MSFC/FA71

7. AUTHOR(S)

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

13. TYPE OF REPORT & PERIOD COVERED
Technical Memorandum
Research and Development, 1974-1982

12. SPONSORING AGENCY NAME AND ADDRESS
The Department of Energy
Office of Coal Mining

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This work was performed under the terms of an Interagency Agreement (ET-75-I-01-9012) between NASA and DOE.

16. ABSTRACT
The Longwall Guidance and Control (G&C) Development Program was begun in 1974 with the aim of determining which systems and subsystems of the longwall system lent themselves to automatic control in the mining of coal. The upper coal/shale interface was identified as the reference for a vertical G&C system, with two sensors (the Natural Background and the sensitized pick) being used to locate and track this boundary. In order to insure a relatively smooth recession surface (roof and floor of the excavated seam), a last and present cut measuring instrument (acoustic sensor) was used. Potentiometers were used to measure elevations of the shearer arms. The intergration of these components comprised the Vertical Control System (pitch control). Yaw and roll control were incorporated into a Face Alignment System which was designed to keep the coal face normal to its external boundaries. Numerous tests, in the laboratory and in the field, have confirmed the feasibility of automatic horizon control, as well as determining the face alignment.

17. KEY WORDS

18. DISTRIBUTION STATEMENT
Unclassified - Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	113	NTIS

FOREWORD

In accordance with established national goals, the Department of Interior (DOI) and the National Aeronautics and Space Administration (NASA) entered into an agreement in January 1975 for joint participation in a program of "Advanced Mineral Extraction Technology." It was stated that coal mining was to be the first priority of these efforts. In October 1977, the management of this program was transferred from the DOI, Bureau of Mines, to the newly created Department of Energy (DOE). Under this program, NASA has utilized its capabilities and technology resulting from the space program to support the advancement of coal mining extraction technology. The work performed by NASA's George C. Marshall Space Flight Center was focused upon research and development of guidance and control systems for automation of the longwall mining process.

ACKNOWLEDGMENTS

NASA/MSFC wishes to acknowledge the assistance and cooperation of the many people and organizations in government, industry, and universities that participated in this program, without whose help the many achievements in this program would not have been possible. The program was under the cognizance of Mr. William Schmidt, DOE, Washington, and directed by Messrs. E. R. Palowitch, Claude Goode, and Michael Pazuchanics of DOE, Bruceton, Pennsylvania.

Appreciation is expressed to the men and mines who made their facilities available for the tests reported herein. In particular, thanks are expressed to Messrs. Howard Epperly and Jim Boulton of the Carbon County Coal Company, Hanna, Wyoming; to Messrs. Ed Moore and Harry Elkins of Kaiser Steel Co., Raton, New Mexico; and to Mr. John Janes of Old Ben Coal Co., Benton, Illinois. These gentlemen and their associates showed the utmost cooperation in carrying out tests in their mines.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

ORIGINAL PAGE IS
OF POOR QUALITY

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

1.0 INTRODUCTION

Under the terms of the agreement with the Department of Energy (DOE), this final summary report of the work accomplished in defining and developing the techniques and equipment necessary to automate a longwall shearer is submitted by the National Aeronautics and Space Administration (NASA). In presenting the problem to NASA, it was anticipated by DOE that the technology arising from the Space programs could be adopted to the general problem of automation.

Initial review of longwall shearer automation by NASA, led to a definition of the problem as one of guidance and control in the classic planes of reference: pitch, yaw, and roll. Additionally, some reference, characteristic of longwall faces, would have to be identified before a guidance and control system could be designed. These considerations led to prioritization of the task into two principal divisions; first, identify a reference with appropriate instruments and, second, define a system for guidance and control. The first task resulted in identifying the coal/shale interface as the reference and the investigation of fifteen (15) instruments thought to be potentially capable of sensing the interface. From these investigations, two (2) instruments were chosen as the most promising, the Natural Background Sensor and the Sensitized Pick. Field testing in coal mines demonstrated their capability to satisfactorily perform the task.

Having defined the reference and instruments to sense the reference, the guidance and control system definition was then specified as consisting of a Vertical Control System (pitch) and a Face Alignment Measuring System (yaw and roll). Variations of the general system were then defined to accommodate a "building block" approach to full automation that would allow an orderly testing and problem solving activity to proceed with mineral risk and resource commitment. Emphasizing the vertical control, the area in which coal mine operators had indicated as the one of most interest to them, aboveground testing began at Bruceton's Mock Longwall Facility. The "breadboard" system was successfully demonstrated in 1978. A contract was subsequently negotiated with Foster-Miller Associates of Waltham, Massachusetts, to convert the "breadboard" system into an experimental "mine-hardened" assembly and test it on an operating longwall shearer. Problems were encountered that delayed the demonstration of the situ tests; however, the assembly was successfully tested at the Bruceton facility.

The Face Alignment System was also successfully demonstrated in a "breadboard" configuration and in a mine-hardened configuration designed by the Benton Corporation. Again problems of finding a suitable coal mine for testing delayed in situ testing.

However, NASA has succeeded in specifying solutions to the problem of automating a longwall shearer, successfully demonstrated those solutions by aboveground testing, and produced mine certified hardware that will ultimately lead to an automatic longwall shearer system.

Details of the technical development are contained in documents cited in the list of references at the end of this report.

2.0 AUTOMATIC VERTICAL GUIDANCE AND CONTROL

In view of the advances made by NASA in space program developments, the Department of Interior requested assistance in adopting suitable technological advances to problems being encountered in underground coal mining. A series of bilateral discussions ensued during which it was mutually determined that an automatic control system for the longwall shearer would be the most promising area in which NASA could work. A cooperative agreement was then signed and MSFC assigned the task by NASA Headquarters. The development of a Face Alignment and a Vertical Guidance and Control System was the result. The justification for wanting to automate certain functions was that, in nearly all cases where automatic control has been introduced, it has proven to be an asset. The first problem investigated was: What system or subsystem best lent itself to automation? After study, the coal-winning aspect of the longwall shearer was chosen. The primary reason for this choice was that the two basic operations involved, horizon control and face alignment, were repetitive actions played out in the same context each time. Increased efficiency in either operation would result in valuable returns in terms of increased health and safety, less contamination of the coal with non-coal, and increased productivity. However, it was recognized at the time, and has since remained an invariable constraint, that the use of automatic control had to be economically and operationally feasible. With either of these constraints relaxed, or eliminated, the way was open to develop an automated system which would probably have little attraction for any prospective user.

After the identification of the areas in which automatic control would be introduced, the following questions, whose answers were deemed essential to the solution of the automation problem, were asked: What measurements are needed? How can they be made? How will they be used? These questions are not independent. For example, what measurements are needed depends on the control scheme adopted. Without recounting the numerous approaches that were examined and discarded, it is sufficient to say that it was decided that the interface of the coal and non-coal would be the spatial reference with respect to which all control would be made; and this is the reference surface to be used regardless of whether coal is to be taken up to the rock or a certain amount of coal is to be left. With this decision made, it then became a question of how rock presence would be determined and how coal depth would be measured, i.e., a search for sensors. Concomitantly, control schemes were being examined to determine what other guidance information would be required in addition to rock presence and coal depth, e.g., arm elevation and downface distance. The evolution of the automatic control system did not proceed with isolated investigations of this or that sensor, but rather with the recognition that guidance and control were not done separately; the needs of one has a direct bearing on the performance of the other. In this way, the development of the hardware and the control algorithms proceeded jointly and dependently.

During the course of the work, it was recognized that there were some longwall faces where automatic control would probably not have an application; or if it did apply, that the environment would require an effort out of proportion with the expected gains. These instances were recognized, and our efforts were directed to those many instances where automation was clearly applicable.

At the outset of this program, it was agreed that the search for sensors and control schemes would be exhaustive, and that any reasonable principle would be investigated. A glance at the types of sensors investigated will indicate the range of principles that have been investigated.

The same approach was used in the investigation of methods of measuring the curvature of the face and determining the location of the endpoints. The latter task is not difficult because of the presence of spads in the entry. The determination of the trajectory of the shearer was, in a sense, made more difficult because there are a number of ways it could, in theory, be determined. All of these approaches were viewed from the standpoint of cost, ease of use, and simplicity.

It is assumed that the basic operation of a double-drum longwall shearer is well-known. The aspect of interest here is that the shearer executes consecutive cutting passes along the face, staying within the coal seam, if possible, but cutting into the bordering rock if required for reasons of headroom, etc. In this program, it was always assumed that coal was to be taken up to the coal/shale interface or up to some prescribed distance (within the coal) from this interface. No provision was made, nor was one required, to provide vertical guidance and control of the drums when the aim was to take a prescribed amount of rock with the coal. Rather, the study centered around that majority of cases where deliberate, continuous taking of rock is not required, and where conditions are relatively benign, e.g., no abnormal protrusions of rock into the seam, no wildly varying interface undulations, etc.

The problem facing the drum operator is that, if he is attempting to take coal up to the interface, there is no way he can know where the interface is until he has encountered it. If the operator wants to cut to the interface, he generally depends on observing the cut directly behind the roof drum for evidence that he has cut to the roof; or if visibility is poor, he can rely on the presence of sparks, or a change in acoustic content. In some mines, there will be a marker (e.g., dirt band) lying within the coal seam which tends to lie a constant distance from the interface. If this band exists, and permits, it can provide the operator with a visual reference with respect to which he can displace the drum and have a reasonable hope that he is cutting along or near the interface. None of these techniques in either case are very reliable. What is needed are sensors which can, with a high probability, indicate the location of the interface, whether coal is to be taken to the interface or a prescribed amount is to be left. This calls for the development of two different types of sensors: one type to determine the presence of rock, the other type to measure a thickness of coal. These sensors are discussed later, in more detail, in this report.

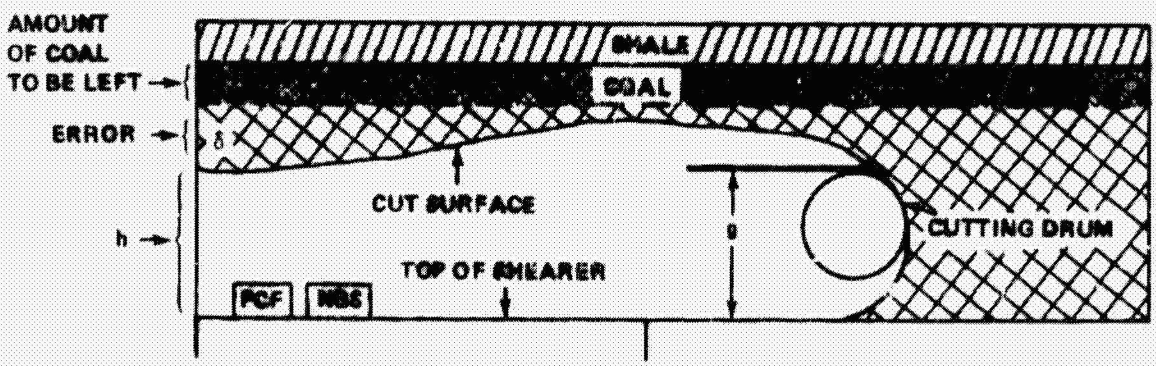
Supposing that sensors to measure coal depth or rock presence are available, how can they be used in a guidance scheme; and what will the guidance scheme (or schemes) be? The possible number of locations that are available and useful is extremely small. No sensor has been devised that can give definite information about the location of the interface where the drum has not cut. Then, we are left only with the information that is available where the drum has cut; and it is within this context that satisfactory guidance and control must be done.

Investigation has shown that a reasonable means of detecting an encounter of the cutting drum with rock exists; this can be done with a sensitized pick. In this case, this knowledge is gained almost as soon as the encounter is taking place. But, this is the only instance where the desired information is obtained in a timely fashion. All attempts to devise a technique where coal depth is measured at the drum (or even in front of it) have been unsuccessful; and, as a result, only the thickness of coal at some distance from the drum can be measured. These measurements can be made behind the drum on the current pass and used then to control the drum, or measurements of the coal thickness on the preceding pass can be retrieved from computer memory and used in controlling the drum's elevation.

ORIGINAL PAGE IS
OF POOR QUALITY

Assume that coal depth will be measured using the most successful coal depth sensor – the natural background sensor (NBS) – and assume that it is mounted on the shearer looking up at the fresh-cut pass. From the point of view of control, the ideal place to mount the NBS would be directly behind the drum. The measurements would be timely; and there would be no possibility of control instability, the measurement being so close to the control quantity. Practically speaking, the NBS cannot be mounted very close behind the drum; in fact, it does not appear reasonable to mount it on the ranging arm. Then we are left mounting it on the end of the shearer and at a distance of several feet behind the roof drum. Because of this distance between the NBS and drum, there is the possibility of poor drum control occurring because of the lack of correlation between the position of the drum and the amount of coal being measured by the NBS. This situation cannot arise if the NBS follows behind the drum closely.

The deleterious effects of having the NBS lag the drum by a relatively large distance can be greatly lessened by knowing the drum's elevation relative to the surface of the coal being measured by the NBS. This is true because, if the error in amount of coal left at one point is known (i.e., the point or area being scanned by the NBS) and if the elevation of the drum's cutting edge is known relative to the surface of measured area, then a suitable command can be given to the drum to decrease the error. This is illustrated in Figure 2-1.



K = amount of coal to be left

K + δ = amount of coal measured by the NBS

h = height of coal above shearer

g = height of drum relative to chassis (obtained from potentiometer mounted on ranging arm hub)

K is known beforehand. δ is determined from $\delta = K + \delta - K$. h is known from the distance sensor which measures the distance from the chassis to the coal surface. Thus, the distance from the chassis to the desired cutting surface is known, as well the distance from the chassis to the top of the drum. Therefore, the position of the drum in relation to the desired cutting line is known. One of the simplest control laws is to compare the elevation of the drum with the elevation of the desired cutting line:

If $g < h + \delta$ command drum up
If $g > h + \delta$ command drum down.

Figure 2-1. Diagram of control algorithm.

The amount that the drum is moved can be proportional to its error in position, but with an upper limit on the maximum excursion for one command. This is done to avoid severe changes in the cut surface of the roof. If the change is too abrupt, it may make the placement of the chock canopy more difficult. Additionally, the control algorithms incorporate a deadband so that if the position error of the drum does not exceed a pre-set amount, no command is given to the drum. This avoids needless heating (with possible overheating) of the drum actuator's hydraulic fluids. A deadband is also required because of the inevitable fluctuations in measured quantities, e.g., the determination of coal depth using the NBS. Because disintegration of nuclei is random, the counts of the by-products fluctuate from one sample to the next. In this case, however, they follow a Poisson distribution.

Thus far, the discussion has mentioned only guidance and control of the roof drum using coal depth measurements from somewhere behind the drum; and it has been appreciated that the greater the distance the sensor lags behind the drum, the worse the drum control will be. A significant improvement can be made if the measurements made by the NBS are stored on one pass and used for control of the drum on the next pass (of course, the NBS operating and having its measurements stored on every pass). Under the scheme, it is clear that there is no correlation between drum elevation and the surface of the last pass cut coal. But the depth of coal adjacent to the drum is known because it has been stored, and all that is needed is to know the elevation of the drum relative to the adjacent cut surface. This can be done using, e.g., an acoustic distance measuring unit. The advantage in using stored data is that a depth of coal is known which is relatively close to the drum, in fact, a drum width away. The disadvantage is that it must be stored as a function of downface distance.

No mention has been made of how the floor drum is to be controlled. Briefly, no reasonable way has been found to measure the depth of coal remaining on the floor after the floor drum has passed. There is too much debris of variable composition, compaction, and thickness to allow successful use of a natural background sensor. If a sensitized pick is to be used, it is doubtful whether a signal could be successfully transmitted through this debris from this pick, assuming there is sufficient difference between the floor clay and the coal for discrimination.

A study was made of the geometry of the interface between coal and the roof and floor. The most important findings were: (1) the floor and roof are generally parallel, (2) they generally undulate in unison, and (3) these undulations are not so severe that they preclude the use of automatic control. With this information, it then became possible to consider slaving the floor drum to a constant distance from the roof. This has been done in one of two ways. One way -- the most direct -- is to mount a distance-measuring sensor (e.g., acoustic) on the arm of the floor drum, have it looking up at the fresh-cut roof, and measure the distance from it to the roof. It is then a simple matter to compare the reading with the desired distance and use the difference as the error signal.

Another way that slaving has been done is to measure (via arm potentiometers) the elevation of the roof drum as the shearer trams, and to store these measurements for each corresponding downface distance. When the floor drum occupies a given downface location, calculate, by simple trigonometry, the floor drum's elevation required to give the set distance from the roof surface. Both of these techniques have been successfully used on the Bruceton mock longwall face using the Joy shearer. A disadvantage of the geometric slaving is that it requires the use of a downface distance sensor and temporary storage of elevations. An advantage is that equipment, such as the acoustic unit, is less likely to be damaged.

In the fully automated system, using the components which have been described, all control commands are done by a computer. All sensor outputs are routed to the computer to be used in the control algorithms, the output of which is sent to the ranging arm valves, which then cause the arm to be raised or lowered. The Joy machine at Bruceton, Pennsylvania, has been completely automated in this sense, and has been run successfully. Figure 2-2 shows the maximum equipment that a shearer having a fully automated vertical control system (VCS) would carry. It is not necessary that all parts shown be installed, because the system allows use of subsystems. Suppose for a particular mine that only the floor cut is presenting a problem. Then an active sensor, such as an acoustic sensor, could be used in conjunction with the computer. Or, if coal is to be left on the roof, a subsystem using the NBS, present-cut sensor, roof arm potentiometer, and computer can be used. Notice that in each instance a computer is used. At the present time, only the NBS and its display is capable of standing alone, i.e., not requiring a separate computer. It is no problem to design a display for the present-cut distance, except that MSHA approval must be obtained.

In view of the possibility that subsystems can be used, and considering the restraint that interference with the normal operation of the shearer on the face must be kept to a minimum during installation and use of the VCS, the possibility of controlling the drums, using the present human operators, has been examined. This is the "man-in-the-loop" (ML) concept which uses the operator, who observes the command issued by the computer, to manually control the drum. This approach uses the man on the face (who will probably be present, anyhow) and greatly lessens the amount of interfacing with the shearer; e.g., it is not necessary to break into the shearer's control valves. Using the above example of controlling the roof drum using an NBS, arm pot and present-cut distance sensor, the ML concept requires that the outputs of these sensors be sent to a computer which, after operations on the data, displays a signal to the operator to go up, down, or leave the drum where it is. Because the computer designed for the automated shearer is relatively large, and certainly larger than required for an ML operation, attention was turned to the use of a smaller package.

As mentioned earlier, it is not necessary that commands be given to the drum at a high rate. Observation shows that operators issue commands sparingly because the interface geometries are relatively benign. This fact lessens the demand for a high-speed computer, and suggests the possible use of a small (hand-held) programmable computer.

This has led to the development of a display/processor (D/P), which consists of a Hewlett-Packard 41Cv computer, a Hewlett-Packard miniature micro-cassette tape recorder,* an Intel 8085 microprocessor housed in an explosion-proof box measuring 10-1/8 in. by 7-1/8 in. by 7-1/8 in. One face of the box contains a window through which the display-lighted colored bulbs can be observed. It's small size allows it to be mounted easily on the shearer, taking up very little room. Since it is battery-powered, there is no need to tie into the shearer's power.

Tests at the Mock Longwall facility using the Joy shearer have been done using the D/P* with extremely satisfactory results. A command signal to the operator every 6 or 7 sec was more than adequate for satisfactory control of the drum.

* The recorder allows the D/P to be used as a data logger to monitor methane, air-flow rate, material flow rate, off-on status of motors, etc. The computer can then analyze the data on the tape and print it on a companion printer. See Appendix.

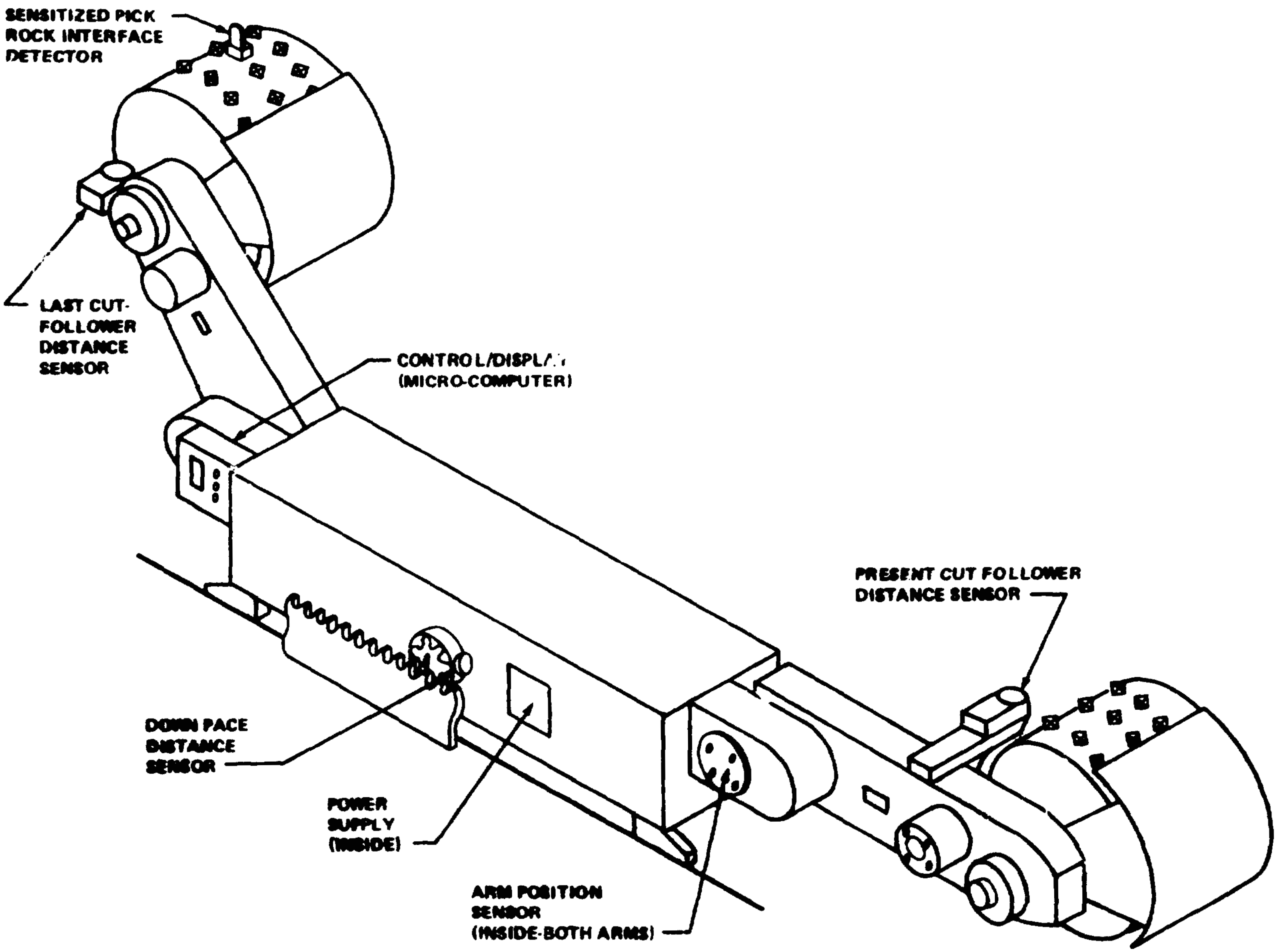


Figure 2-2. Vertical control system - primary components.

3.0 SENSOR RESEARCH AND DEVELOPMENT

3.1 Coal Interface Sensors

Identification and development of viable sensors which would detect the interface between the coal and rock at the seam boundaries was an obvious necessity for any system designed to control coal cutting. Therefore, this effort was given first priority in the development program. Many sensing concepts, encompassing almost all of the known physical principles, were selected for investigation. As shown in Table 3-1, Group I shows those concepts finally selected for experimental development and in-mine test. Group II is those concepts which showed considerable promise but were not chosen for the system for various reasons, such as limited performance, practical considerations relating to design, cost, mine use, etc., or extent of further development required to achieve an acceptable sensor (cost, time, development risk, etc.). Group III is those concepts eliminated early in the investigations because they were shown not to be technically feasible.

Results of the sensor investigations and development are summarized in the remainder of this section.

3.1.1 Natural Background Sensor (NBS)

It has been known for several years that shale and other rocks contain radioactive isotopes, generally potassium and uranium. For somewhat longer, it has been known that the flux of emissions, in this case gamma rays, is predictably attenuated by coal. This situation is illustrated by the shale lying above or beneath the coal seam. By counting the number of events per unit time that a scintillation counter receives when it is placed near a layer of coal which is backed by shale, and using a calibration table or curve, a very good estimate can be made of the thickness of the interposed coal.

Several models of the NBS were developed. Differing mostly in geometry, all utilized the basic components of a sodium iodide crystal and a photomultiplier tube plus various displays. The final model used in the underground test program consisted of a 4 by 8 in. crystal with a thick lead shield surrounding the crystal but leaving a small surface exposed. Figure 3-1 illustrates the basic design configuration of the NBS; Figure 3-2 shows the effect of collimation on the field-of-view. As the distance of the NBS from the roof increases, the length of the collimator must be increased to maintain the same viewing field. The photograph (Fig. 3-3) shows the 4 by 8 in. model in test on the MSFC laboratory simulator. Some of the considerations affecting the NBS design and operation are discussed in the following paragraphs.

Generally, the accuracy achievable with an NBS is proportional to the length of time that counts are made. If the counting time is increased K-fold, then the standard deviation of the spread of the measurement is decreased by the factor $1/\sqrt{K}$. For example, if a given counting time is quadrupled, the standard deviation is decreased by the factor $1/\sqrt{4} = 1/2$. This inevitable spread results from the fact that the disintegration process is a random one; and the distribution of the counts result from this, not from any inaccuracies in counting. The distribution of the counts follows the Poisson distribution, making calculations simple since the standard deviation is the square root of the mean.

TABLE 3-1. COAL INTERFACE SENSOR CONCEPTS

Group	Technique	Measuring Principle
I	Natural Background Radiation	Measures the natural radiation flux emanating from shale. Coal thickness determined by attenuation of the radiation.
I	Sensitized Pick	Generic term for a sensitive element located on the cutting drum. Typically located on an instrumented pick: rock encountered is signaled by a larger force or change in vibration characteristics of the pick (as measured by strain gauge or piezoelectric element).
II	Nucleonic	Detection of the difference in response of coal and noncoal to a radiation source. Difference in backscatter radiation detected by the receiver indicated depth of coal.
II	Electromagnetic (Radar)	Detection of the boundary of coal and non-coal, making use of an electromagnetic receiver and transmitter. Continuous wave, monopulse, or sweep signals are broadcast at the roof and reflect information gathered at the receiver.
II	Magnetic Spin Resonance	Depends upon the presence of free electrons in coal but not in shale. Interacting an RF and magnetic field to each other. At the shale/coal interface, the signal amplitude drops: this is used as the interface locator.
II	Acoustics	The measurement is based upon detecting the reflection of an ultrasonic echo from the coal/shale boundary.
II	Hydraulic Drill	Based upon the water jet cutting through coal but not roof rock. Coal thickness determined by mechanically measuring depth to cut.
II	Reflectometer	Detection of a coal or non-coal surface, using a light sensitive detector to measure differences in surface reflectivity.
II	Penetrometer (Impact)	Use of an instrumented penetrometer whose acceleration profile indicates coal or non-coal encountered as it penetrates.
II	Penetrometers (Saw and Drill)	Use of mechanical means to penetrate coal to the interface. Change in motor current/rpm or vibration indicates when interface is reached and the depth of the coal.
II	Vibration Sensor	Identifies coal or shale material by measuring the vibration of the drums as they are cutting. (Sensor is mounted on shearer's arms.)
III	Electrical Capacitance	Based upon the principle that coal is a mixture of dielectric materials.
III	Electrical Conductance	Based upon the electrical conductance of coal and possible changes in conductance properties arising from layered characteristics of coal seams.
III	Infrared	Possible differences in infrared radiation characteristics of coal and shale.
III	Thermally Sensitized Pick	Possible existence of thermal gradient when cutting coal and shale.

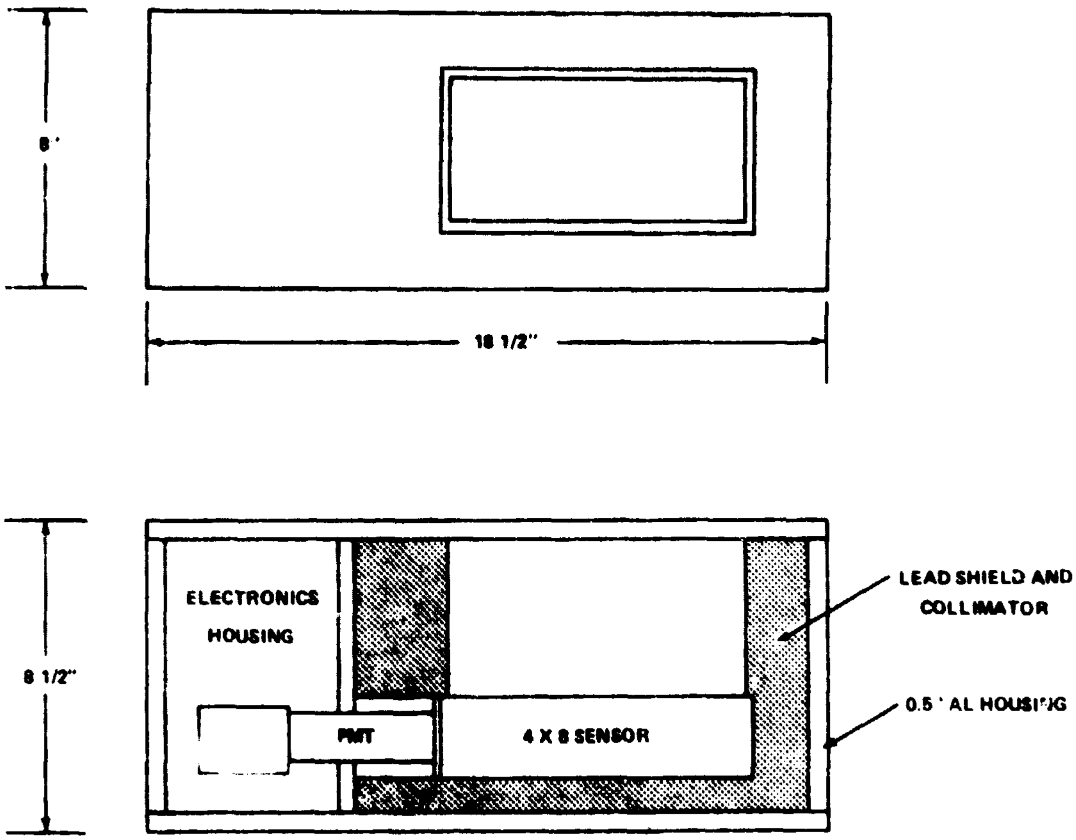


Figure 3-1. Natural Background Sensor (NBS) 4 by 8 sensor package.

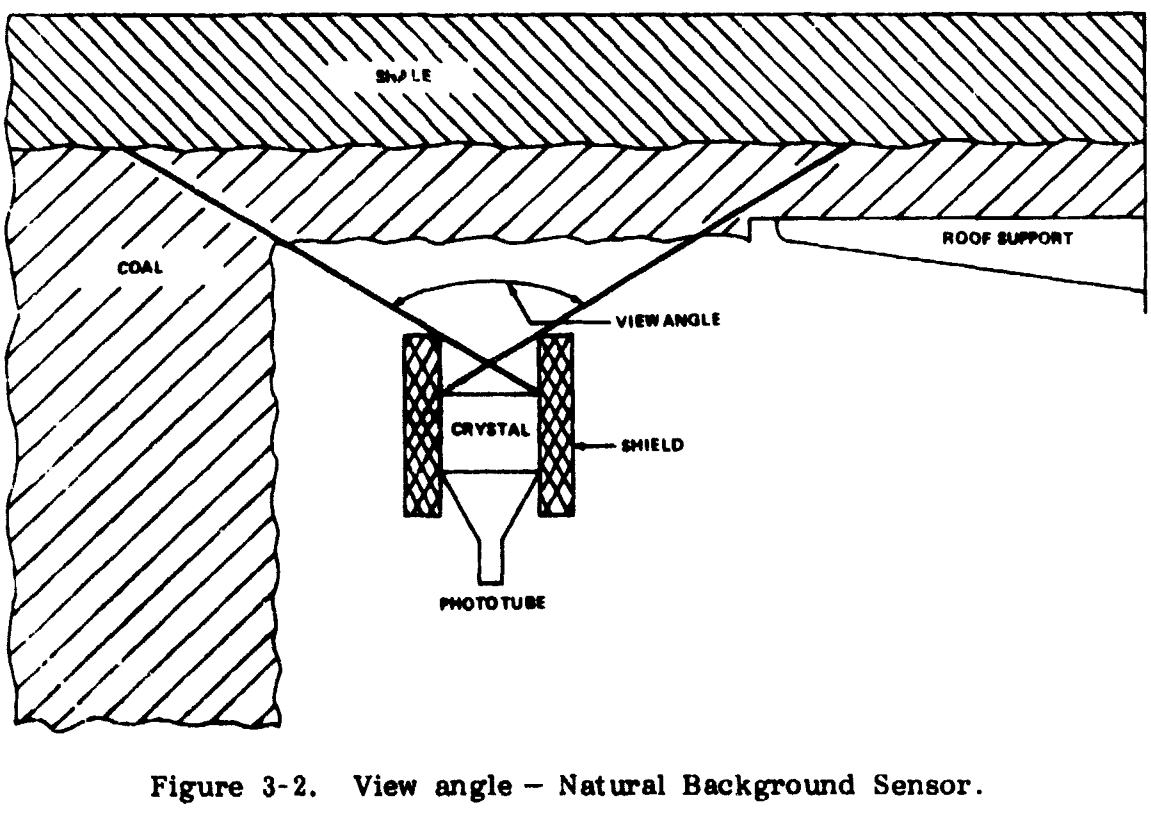


Figure 3-2. View angle – Natural Background Sensor.

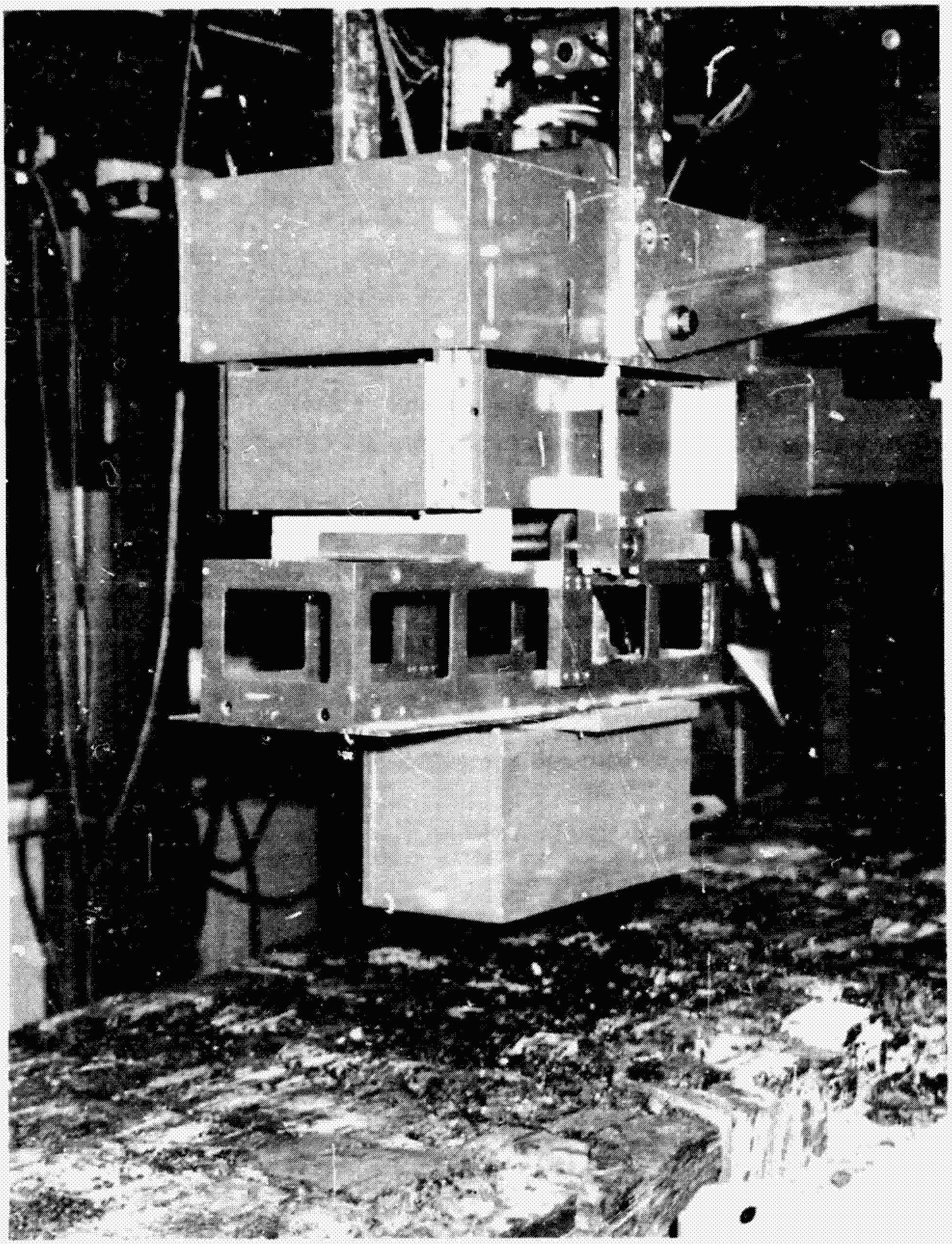


Figure 3-3. Natural Background Sensor mounted on MSFC test fixture.

Radiation originating in the shale is attenuated by the intervening layer of coal in a predictable manner, which can be characterized mathematically as follows:

$$y = ae^{-bx} + B \quad ,$$

where

B = the measured background radiation (in counts per unit of time)

a = radiation of bare shale (counts per unit of time)

b = absorption coefficient

x = coal depth, in inches

y = total counts per unit of time (e.g., for zero in. of coal, $y = a + B$).

Note: The unit of time should be the same.

It is necessary to determine a, B, and b for each coal mine in which the NBS is to be used. In those cases where high energy and low energy shales are interfused, it is necessary to construct a composite curve, taking into consideration the critical values of each. The resulting measurements, while not precise in either high or low energy shale measurements, will be sufficiently accurate for guidance and control purposes.

The NBS has been employed in numerous tests in the laboratory and in the field. The field tests encompassed both static tests and dynamic tests where the NBS was mounted on a mining machine.

The laboratory simulator at MSFC (Fig. 3-3) was a particularly useful tool in the determination of some of the initial design parameters, such as collimator and shielding requirements. The simulator bed was constructed of concrete made with a calcium silicate having a slightly higher natural radiation than shale, so that the resultant mixture approximated shale. Layers of coal or micarta (similar density to coal) were placed over the bed to simulate various coal thicknesses.

Static tests were conducted at the Bureau of Mines experimental coal mine in Bruceton, Pennsylvania, as well as several commercial mines. The tests at Bruceton were particularly valuable in that conditions for the test could be better controlled. Steps of varying coal thickness could be established at the roof and data taken while other parameters, such as count time and distance of the sensor from the roof, were varied. Figure 3-4 shows the mine test set-up. Figures 3-5 and 3-6 show typical data obtained during these tests. The effect of count time on data smoothing can be seen. Notice that the smoothed data provided quite accurate indication of the coal depths (generally within an inch, except at the steps). At the step, that is, where a major change in coal thickness occurred, the NBS read the average depth of the two thicknesses, since its field of view encompassed both areas.

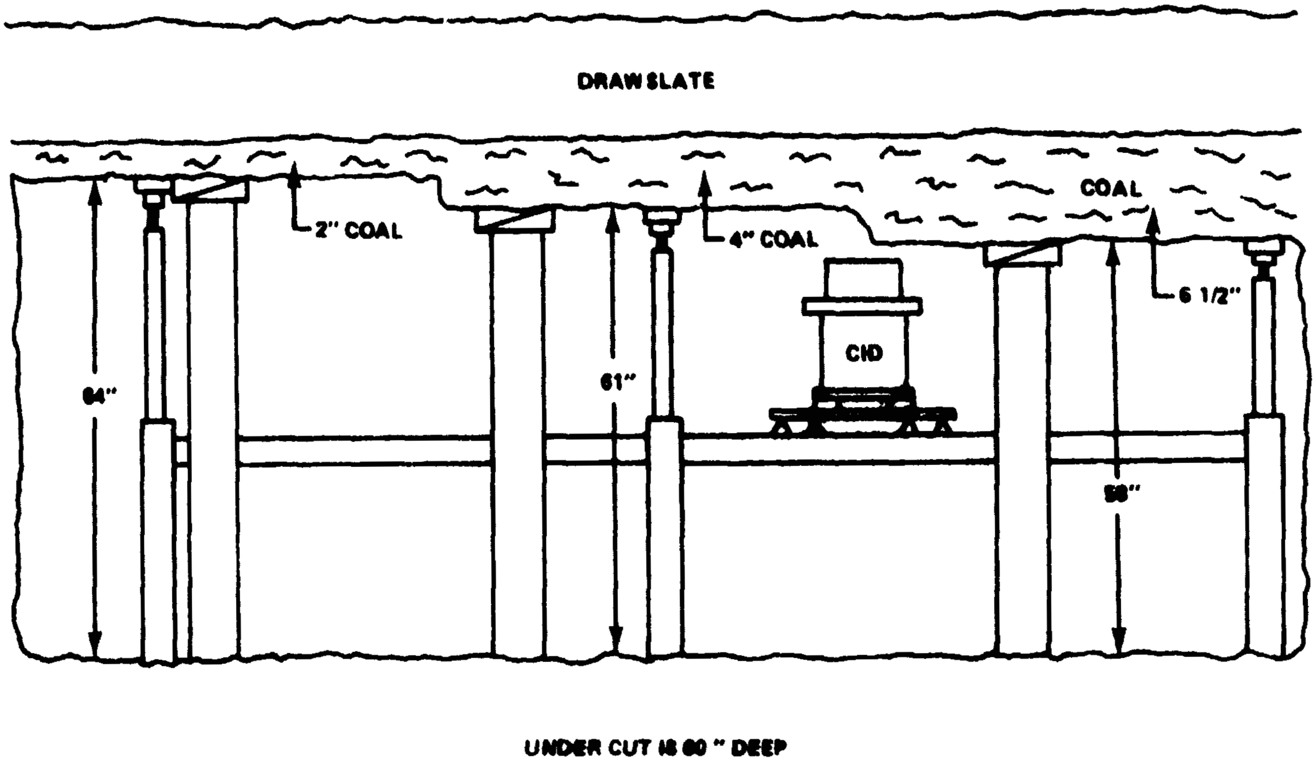


Figure 3-4. In-mine test site Natural Background Sensor.

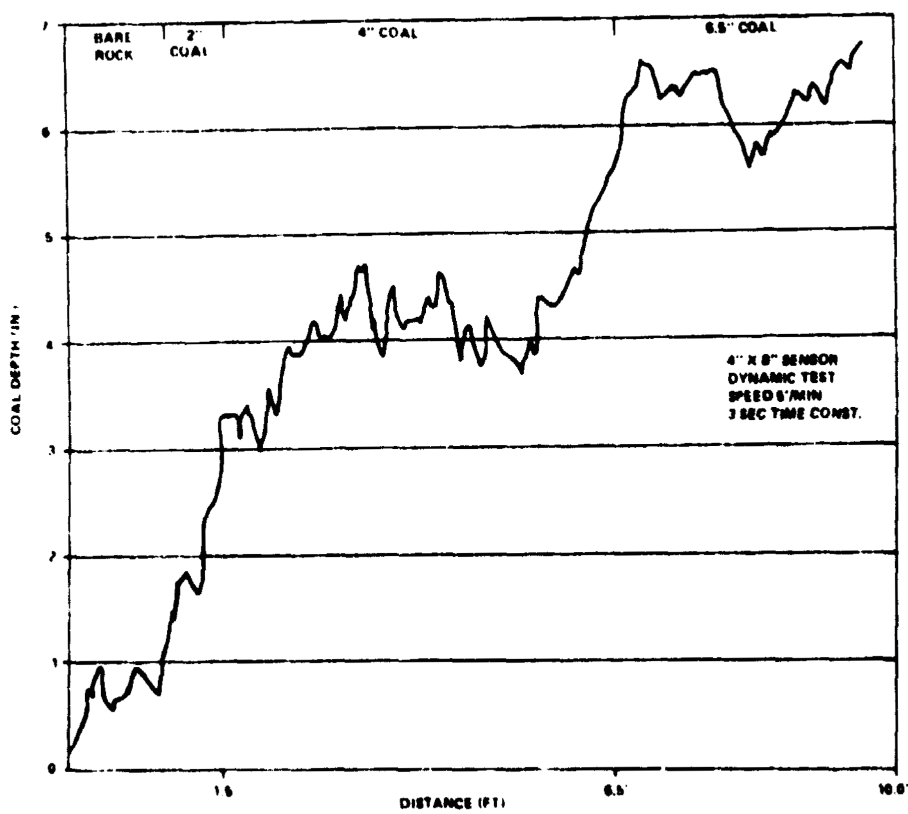


Figure 3-5. Results of Natural Background Sensor test.

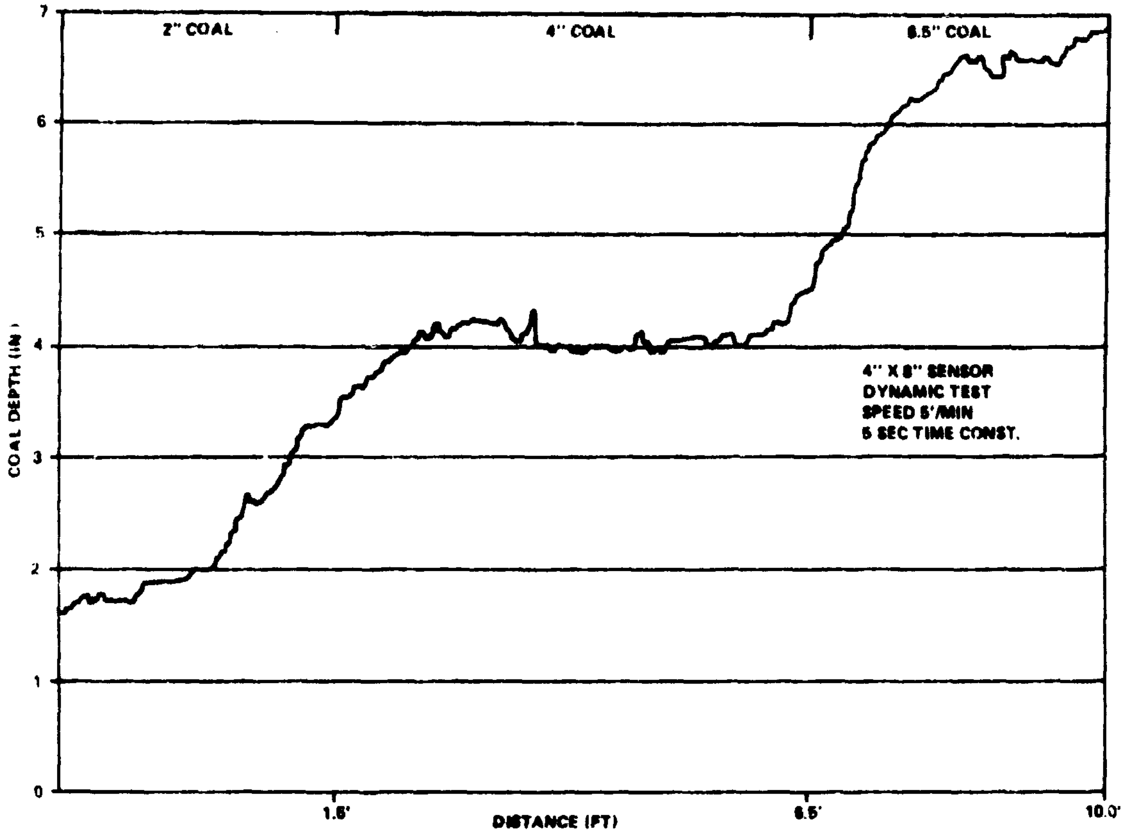


Figure 3-6. Bruceton test results (NBS).

A longwall mine test of the NBS was conducted at the Kaiser Company's mines in Raton, New Mexico, by General Electric Company and MSFC personnel. Figures 3-7 and 3-8 show the calibration curves for both the sandstone and shale roofs encountered. A photograph (Fig. 3-9) shows the NBS mounted on the Anderson Maver shearer. Note that a high-impact plastic debris shield was installed on the NBS. Although the test successfully demonstrated the NBS's capability to correctly measure residual coal thicknesses and to withstand the rigors of the machine environment, seam geology prevented measurements along the total face.

The NBS was also tested as an operator aid in conjunction with driving longwall entries. In the first case, an NBS was tested for about 2 weeks at the Old Ben Coal Company in Benton, Illinois, on an entry boring machine. In this particular entry (mine No. 26), Old Ben desired to determine if a minimum of 8 in. of coal could be left in an arched configuration on the entry roof. If so, this could possibly reduce roof bolting requirements and speed entry development. The NBS was able to provide accurate roof coal measurements as determined by drilling through the roof coal to the interface (the previous method being used). Also, the NBS (both sensor and display) was able to withstand the rigors of the machine. However, because this test unit was battery-operated (not MSHA approved for machine power connection), it became obvious that the routine of recharging and changing batteries was not satisfactory (nor was it ever intended to be) for continuous production operations.

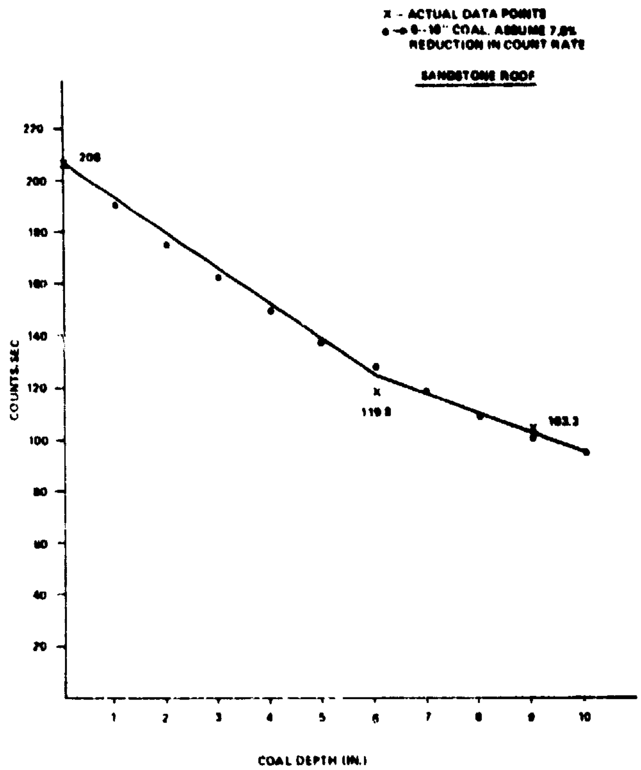


Figure 3-7. York Canyon mine calibration (NBS) (sandstone roof).

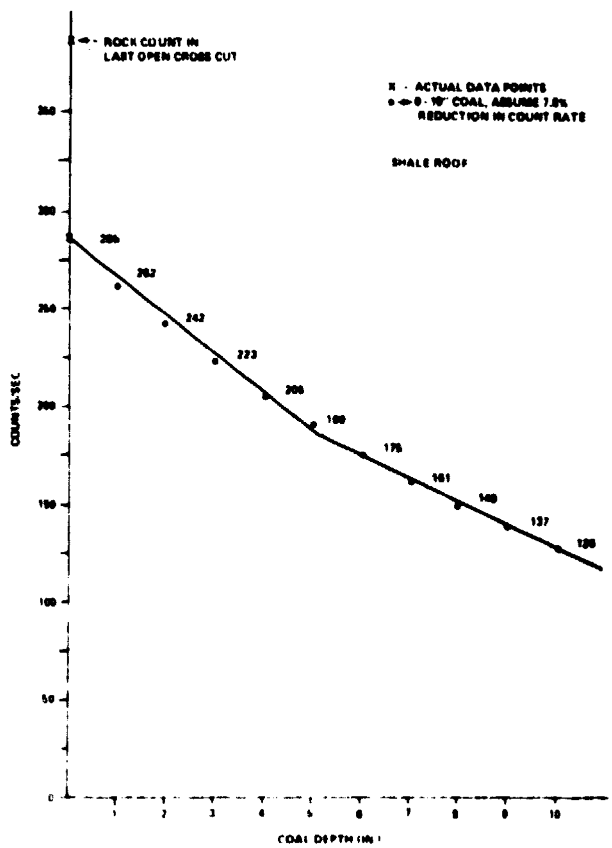


Figure 3-8. York Canyon mine calibration (NBS) (shale roof).

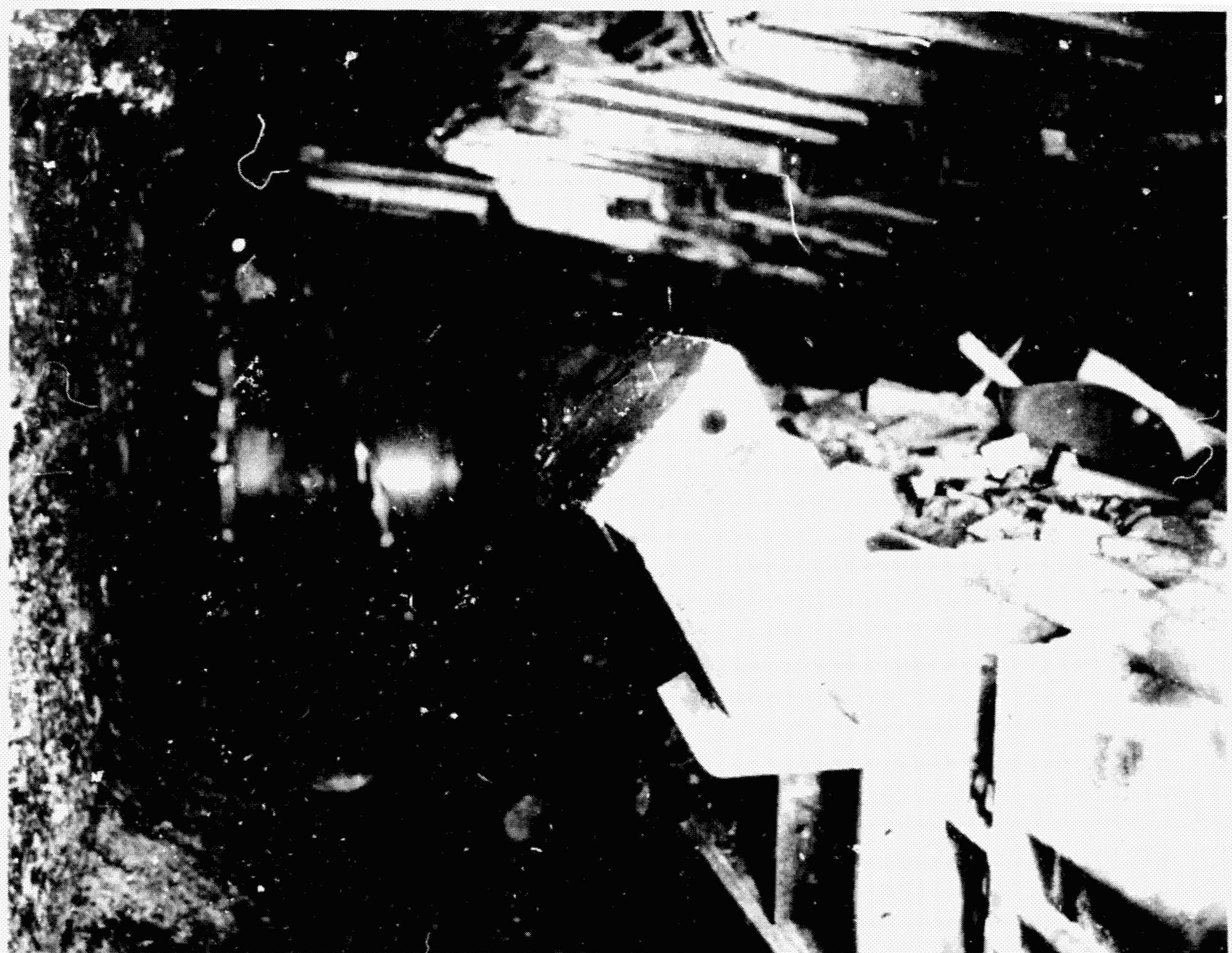


Figure 3-9. NBS mounted on air operating longwall shearer.

Tests of the NBS were also conducted at the Carbon County Coal Company (CCCC) in Hanna, Wyoming, on a Joy 12CM continuous miner used for longwall entry driving. The composite (Fig. 3-10) depicts the location of the sensor and display/signal processing unit on the Joy machine. (This is not an actual photo of the Carbon County mine, but was graphically constructed to show the concept of the operator monitoring the display while the sensor reads thickness of roof coal left in the previous cut.) The problem at CCCC is that a 14-ft cut is being made in a 20-ft seam, leaving about 2 to 3 ft of coal on the roof and the remainder on the floor. Since neither the roof nor the floor is conveniently available for a navigational reference, it is quite difficult to know where the cutting is taking place. Drilling of the roof coal is the only method currently available. This results in a very uneven roof and floor, with large steps in places where major readjustments are necessary. The CCCC condition was quite a challenge for the NBS, as its design had not been intended for depth ranges much over 10 to 12 in. It was expected that its accuracy in ranges of 2 to 3 ft would be no better than ±6 in. (versus ±1 in.). However, in the CCCC case, this accuracy would be quite acceptable and far better than what was currently being achieved. Calibration tests were conducted at various locations in the mine and for several days with the NBS mounted on the miner. It was discovered that two types of shale existed in the mine, as represented in the calibration curves of Figure 3-11. A compromise calibration curve (between the two shale values) was selected for future testing. It is believed that this will still result in acceptable accuracy for the CCCC case.

Again it was evident that battery operation, although adequate for a single test, was not suitable for prolonged production operations. The NBS equipment showed no significant structural damage after being mounted on the Joy miner for over 2 weeks. However, moisture entered the NBS unit, causing corrosion of electrical components and faulty operation. This has been corrected by waterproofing the sensor's electronic components.

In addition, a new collimator was made for the sensor, and the display/electronic processing assembly was replaced with a smaller display panel and separate electronics unit, as shown in Figure 3-12.

As alluded to elsewhere in this report, the NBS was tested extensively on the longwall shearer at the Carbon County Coal Company Mine in Hanna, Wyoming. Their Eickhoff 300L shearer is operating in a seam whose thickness can vary, over long distances, from approximately 16 to 30 ft. However, such variations are not experienced across the face. Because of BTU content, it is desirable to take the coal close to the roof; but, because exposed shale tends to fall away between the face and canopy tips, causing lengthy delays, it is necessary that a relatively large amount of roof coal be left to avoid this problem. Because there are no reliable natural references on the coal face, such as a binder, unaided horizon control results in undetected drifts of the horizon until either the roof or floor is encountered.

Prior to mounting the NBS on the Eickhoff, extensive calibrations had been made of the roof shale. It was found that there were two distinctly different levels of radiation present, depending on which of two types of shale was being viewed. Figure 3-13 shows (curve 1) the exponential regression curve fitted to the data for the low activity shale. The correlation coefficient is -0.966, indicating excellent agreement between the data and the function $e^{-ax} + b$. Also shown (curve 2) is the calibration curve for the higher activity shale. The background count, 115 in these experiments, was determined by placing increasing amounts of plates of lead and steel around the sensor until no statistically significant changes were noted in the

count data. It should be noted that the background count depends heavily on the shielding provided with the sensor, the sensor electronics, and the amount of shielding provided by the mounting location, e.g., the shearer chassis, etc.

Because it is imperative that the roof not be exposed, it was decided that the shearer-mounted NBS be calibrated for the lower activity shale, thus insuring that the roof coal left would always be no less than that determined by the NBS. If high activity shale was being viewed, then the error would be some 6 inches or so on the conservative side.

The NBS was mounted atop the shearer approximately midway the long dimension and tilted slightly toward the face so that the desired present cut was being viewed. This position was chosen because it interfered the least with operations. Because of the height of the seam, the NBS was located some 5 feet or so from the coal surface being viewed, thus unavoidably allowing some of the face to be viewed as well as portions of the canopy tips. The net result of this was to decrease the number of counts. A new calibration curve with the NBS mounted on the shearer was obtained by comparing the NBS readings with borehole measurements; in this manner, curve 3 was derived. It will be noted that the base count is considerably lower, due principally to the inclusion of the tips and face in the field of view. Again, an exponential regression was done on the borehole data with a resulting regression coefficient of -0.984, indicating outstanding agreement.

The NBS has been operating on the shearer for some 2 months and continues to give consistent results. While no damage has been suffered by the NBS, some repairable damage has been done to auxiliary equipment.

3.1.2 The Sensitized Pick CID

The sensitized pick, a coal/shale interface detector, depends upon the cutting force differential of coal and shale for interface recognition.

The initial configuration consisted of the following components: (1) a special pick block and mounting assembly that is attached to the outer perimeter of the shearer's cutting drum, (2) a load cell (housed in the pick block), (3) transmitter assembly (housed in the pick block), and (4) receiver assembly, signal processing electronics, and power supplies. For test purposes, a tape recorder was provided to record pick signals. This configuration used a telemetry link for data transmission, while the configuration used for the Foster Miller vertical control system uses slip rings for "hard-wire" data transmission.

In operation, the pick encounters coal or shale which deflects the pick and forces its shank to exert pressure on the strain gauge, which in turn initiates a signal for varying amplitudes depending upon the force exerted. This signal is then passed through a series of circuits, which process the signal into discernible patterns characteristic of coal and/or shale cutting forces. Shale, being tougher, generates a cutting force higher in amplitude than coal; hence, recognition of the material being cut is achieved.

As already briefly mentioned, the instrument consists of two basic components: the pick mounting fixture located on the drum and the receiver/processor located on the body of the shearer.

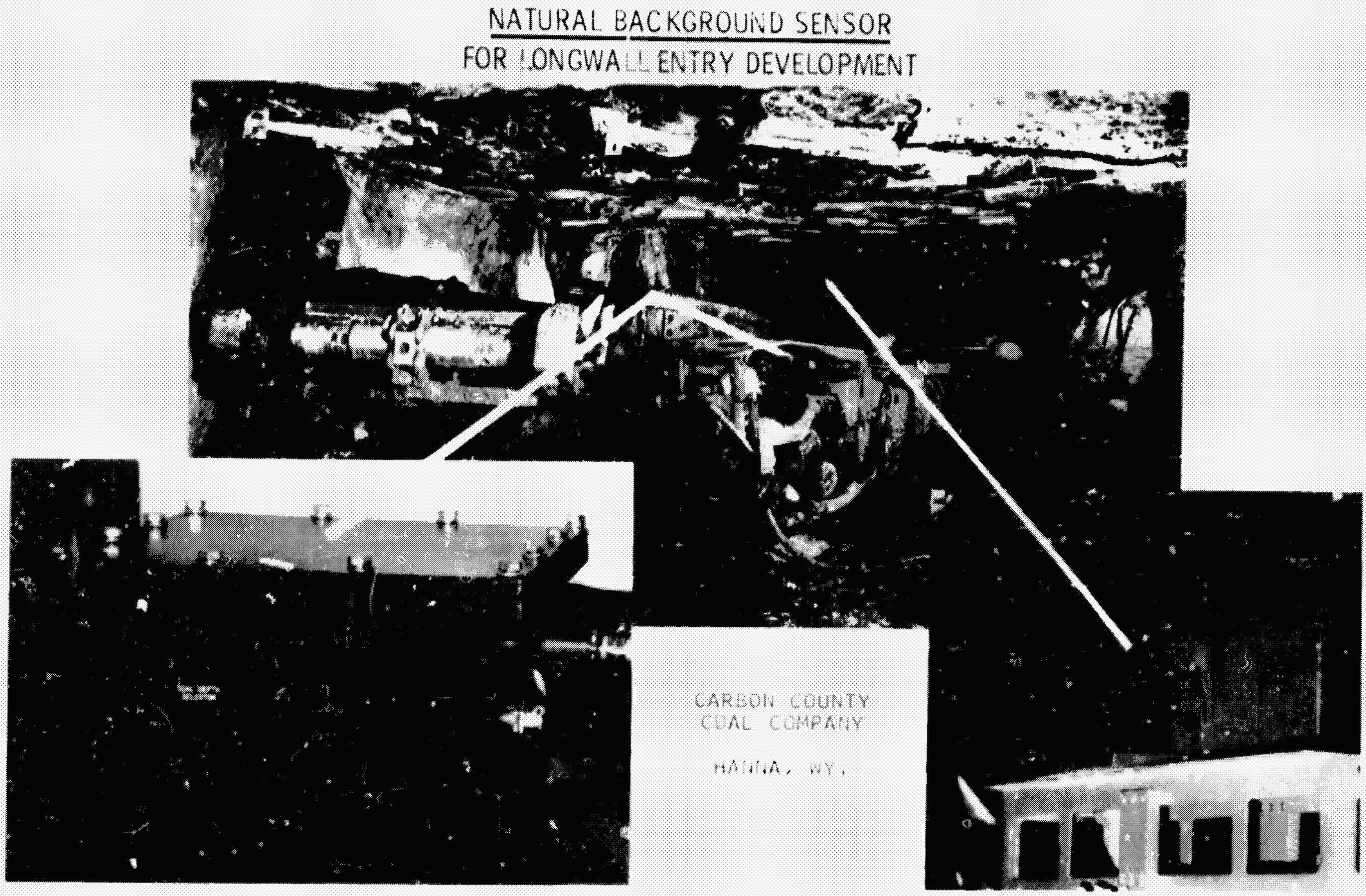


Figure 3-10. Montage of an NBS mounted on a continuous miner.

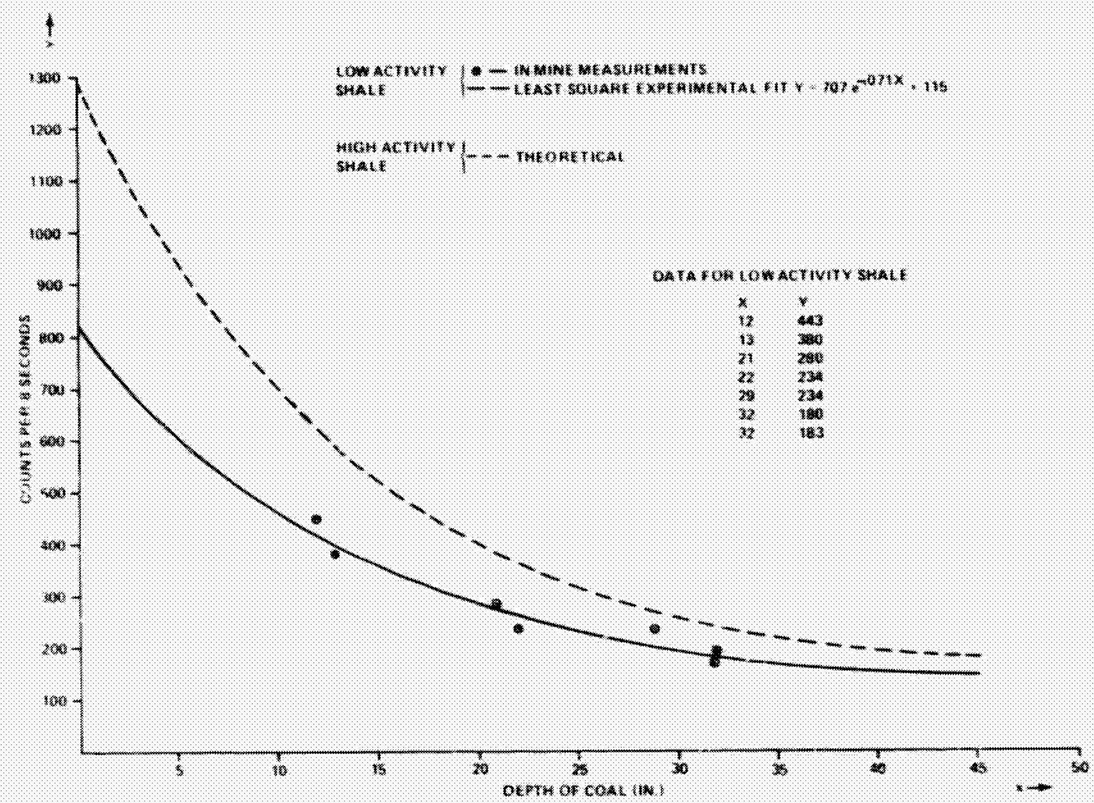


Figure 3-11. NBS calibration curve for Carbon County Coal Company's mine.

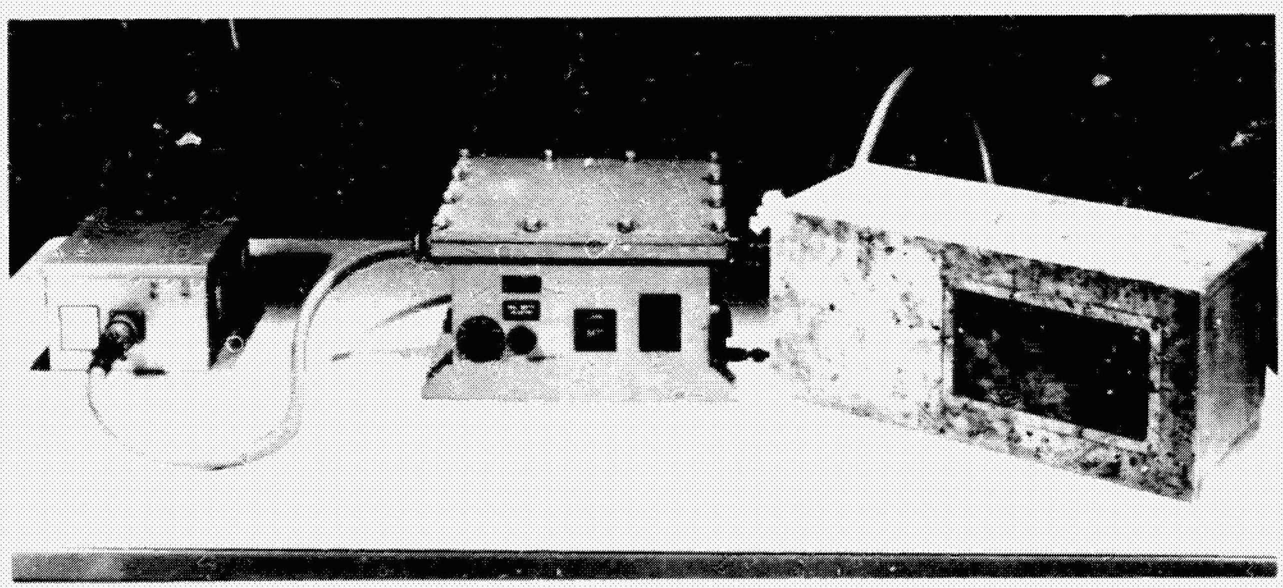


Figure 3-12. 4 by 8 NBS hardware.

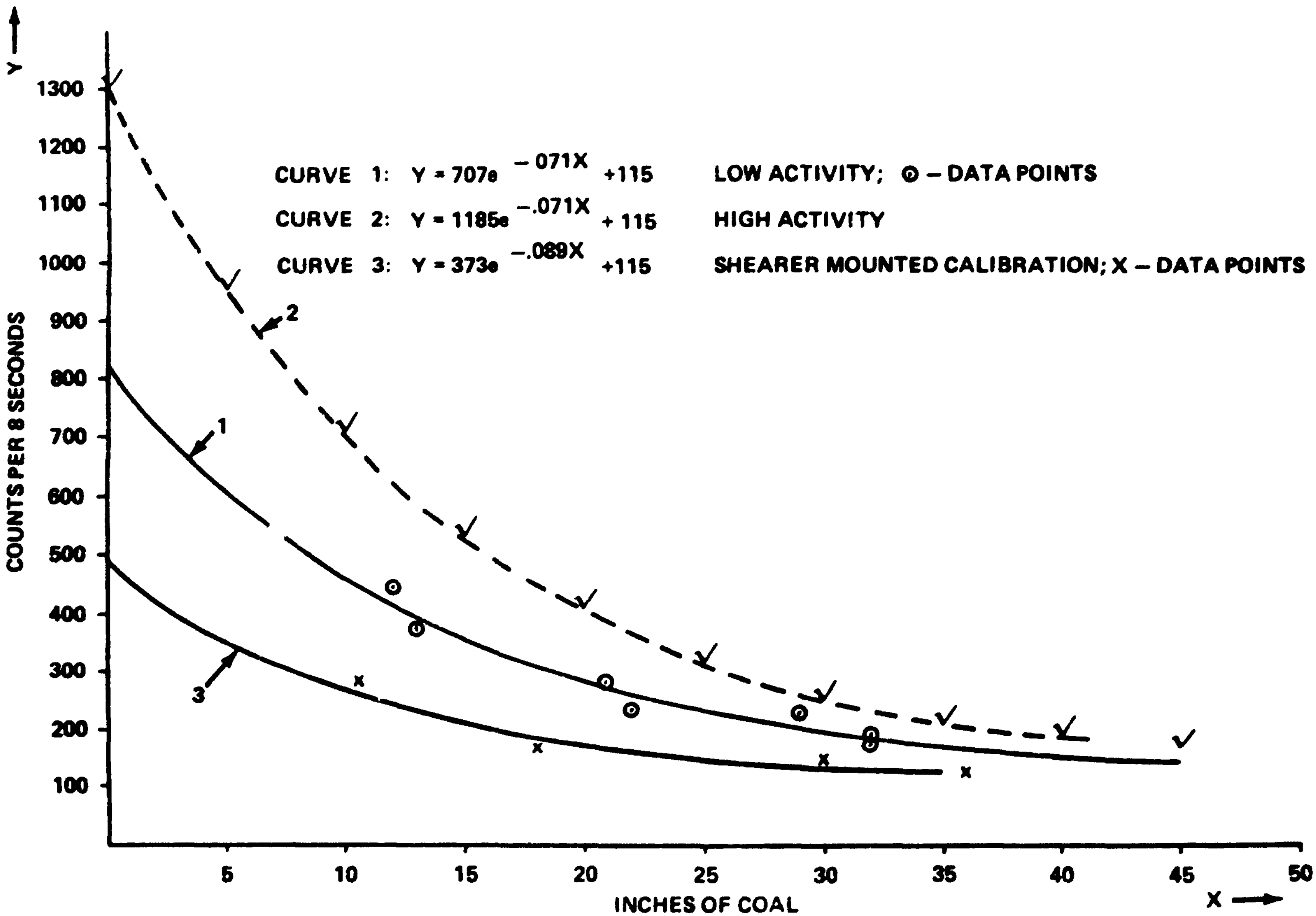


Figure 3-13. Calibration curve of Carbon County Coal Mine using the NBS.

The mounting fixture (Fig. 3-14) consists of two steel housings mounted within the drum vanes, between the scrolls, 180 degrees apart. The fixture contains the pick, strain gauge, transmitter, and transmitter batteries. The transmitting antenna is mounted along the vane external to the fixture. The pick block is bolted onto a 1/2-in. thick steel plate. The plate is welded to a 4-in.-square steel tube having a 1/4-in. wall thickness. The steel tube is telescoped into a 4-in.-square tube. On-site assembly was performed by welding the tube assembly/mounting plates on the drum surface, then inserting the 4-in. tube assembly, adjusting its height, and usin a set screw to secure the assembly for welding. The trailing face of the assembly has a 3 by 5-in. opening for access to an internal compartment in which the transmitter and batteries are located. Cover plates are added to seal the compartment.

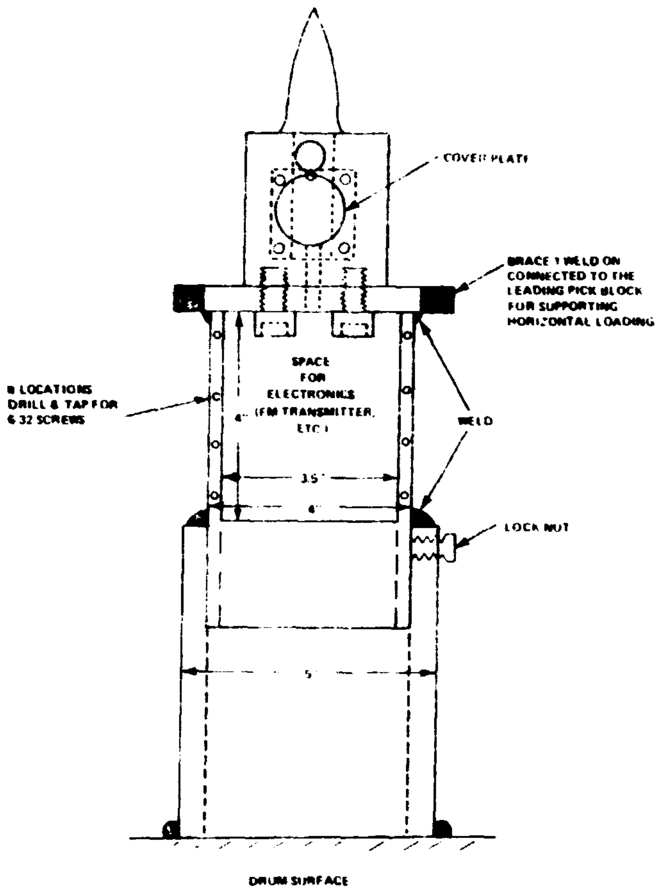


Figure 3-14. Sensitized pick assembly.

The load cell consists of a steel cylinder on which two foil strain gauges are positioned axially. These are connected to two dummy gauges forming a four-arm bridge. This bridge has a theoretical strain sensitivity of 3.48×10^{-8} V/psi/driving voltage, or for the 3/8 in. diameter sensing element, 0.31×10^{-6} V/lb/driving voltage. The sensing element – the steel cylinder – was designed to withstand 10,000 lb compression. Laboratory tests, using a hydraulic loading machine, measured the actual sensitivity of 0.35×10^{-6} V/lb/driving voltage, or 11.5 percent above the theoretical values.

The telemetry system consisted of an INMET T20B, FM-FM transmitter, and an INMET R-10B receiver. The transmitter consisted of a bridge amplifier, a subcarrier oscillator (SCO), and an FM radio transmitter (Fig. 3-15). In operation, the frequency of the SCO is modulated by the bridge amplifier's output voltage. The resultant is an FM modulated signal with a center frequency of 10 KHz. The modulated SCO output is then used to modulate the frequency of the radio transmitter. There are two adjustments on the transmitter: (1) the center frequency of the SCO can be varied to effectively balance the bridge, and (2) a tuning slug in the RF transmitter can be controlled to set the RF center frequency.

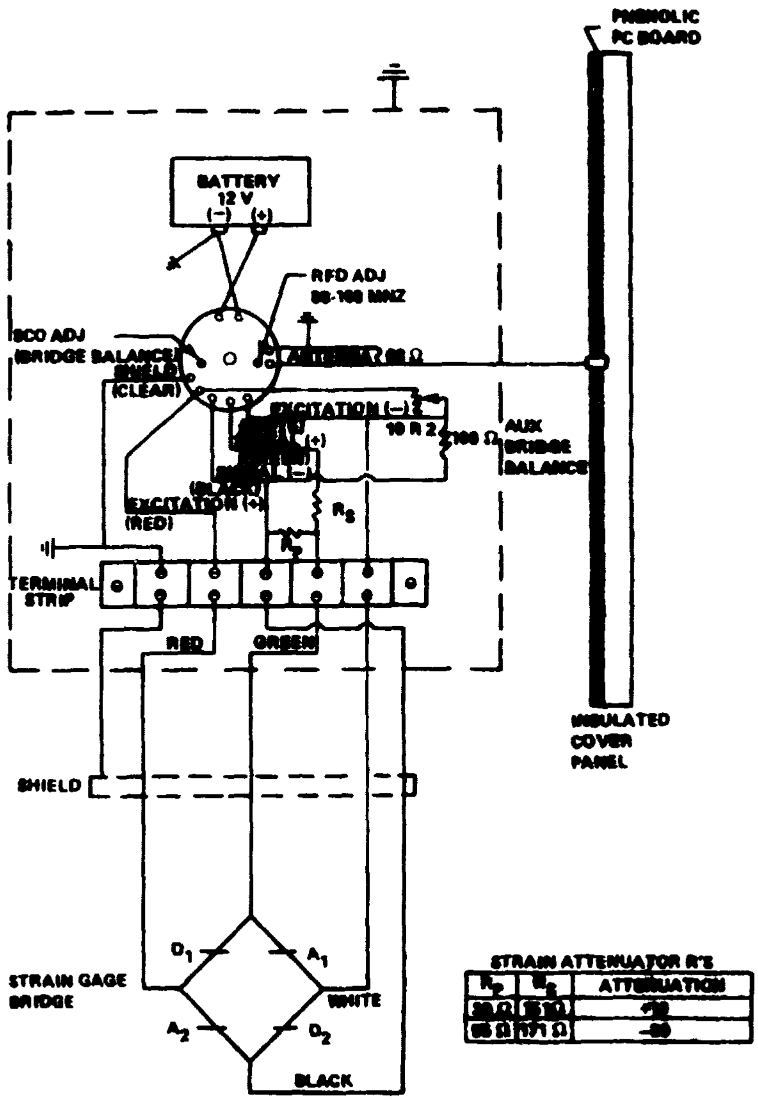


Figure 3-15. T20B strain gage transmitter (FM-FM).

The receiver was tuned to match the transmitter and demodulate the received signal twice to obtain the desired strain signal. First, the RF signal was demodulated to recover the SCO, which was demodulated again to obtain the strain signal.

There were two outputs from the receiver: (1) the SCO and (2) strain signals. The receiver has gain and zero controls which affect the relationship of the strain output voltage to the frequency of the SCO. These were adjusted to obtain the desired calibration at the receiver output.

A quarter wave-loop antenna (Fig. 3-16) was used in the transmission system, which was easily retrofitted along the vanes of the cutting drum. The RF signal strength, measured at the shearer's arm hinge point using a whip antenna, was found to vary between 800 and 4,000 μv depending on the drum's phase angle (Fig. 3-17).

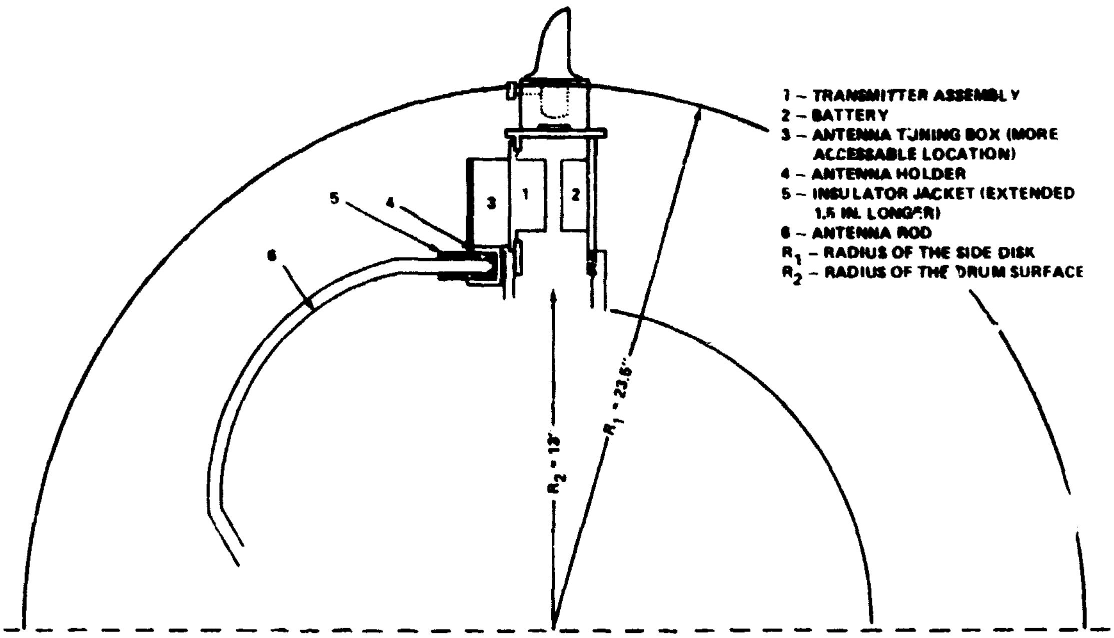
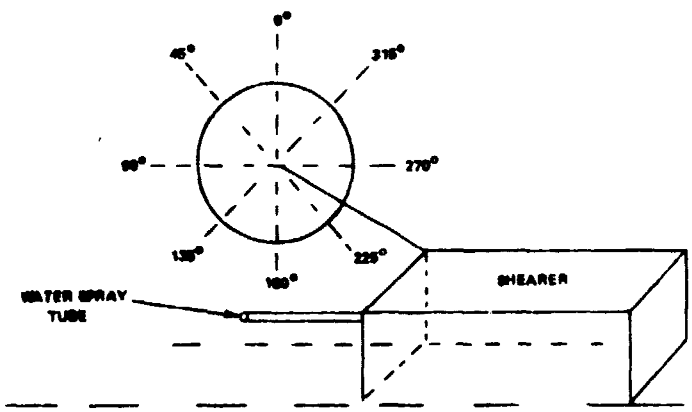


Figure 3-16. Quarter wave-loop antenna for sensitized pick.



DRUM PHASE ANGLE (DEGREE)	SIGNAL STRENGTH (μV)
0	2000
45	700
90	1700
135	2000
180	1000
225	4000
270	4000
[illegible]	[illegible]
315	4000

Figure 3-17. RF signal strength measured in York Canyon mine during scout trip.

The Signal Processor

The signal emanating from the strain gauge is processed through an electronic circuit whose output is a control signal that goes to a controller and secondly a signal which energizes a set of red and green lights (red for rock and green for coal), giving visual information to an observer as to the material being cut.

The processor design is based on the assumption that forces exerted on the pick will be higher when cutting rock than they are when cutting coal. These forces are sensed by a strain gauge whose output is a proportional electric voltage. The cutting signal occurs for only that period of time when the sensitized pick is cutting, or for approximately 1/2 of a revolution of the drum. As cutting occurs, the coal fractures, the signal level will decrease and then increase as the tool again impinges on the coal. The amplitude and frequency of these signal level variations depend upon the prefracture characteristics of the coal and the speed of the drum.

When the cutting drum goes beyond the coal seam boundary, into the overlying shale or rock, the signal level increases. For example, if the normal cutting picks are at the coal/shale boundary, and the sensitized pick extends into the shale, the angle subtended by the arc generated by the sensitized pick is:

$$= 2 \cos^{-1} \frac{R_{NP}}{R_{SP}} \quad ,$$

where

R_{NP} = normal cutting radius

R_{SP} = sensitized pick cutting radius.

If the normal cutting radius is 2-1/2 ft, and the sensitized pick extends 1/4 in. beyond, the angle, θ, is about 15 degrees or about 4 percent of a revolution (360 degrees).

The method of detection (Fig. 3-18) amplifies the signal and removes the noise by allowing only those frequency components below 100 Hz to pass. The remaining signal was input to 10 comparators. When the signal was small, only the lower level LED's were energized and only during the period when the pick was cutting. The higher levels were on for much shorter periods of time. This detection method is sensitive to the speed of the shearer; higher speeds produce higher signal strengths. Five light-emitting diodes (LED's) are excited at 0.2, 0.4, 0.6, 0.8, and 1.0 V, respectively. The higher signal strengths excite five LED's at 1.2, 2.4, 3.6, 4.8, and 6.0 V. There was also an adjustable level detector that excited additional LED's. The output of the comparator was available for signal recording and had a 5.0 V output when the red light was burning.

A second method of detection independent of shearer speed was also used, which uses a low-pass filter to improve the signal-to-noise ratio. Both the peak and the average levels are measured when the sensitized pick is cutting. The peak level is divided by the average value. If the speed of cutting is varied, both peak and average signal values vary by approximately the same percentage. Therefore, the

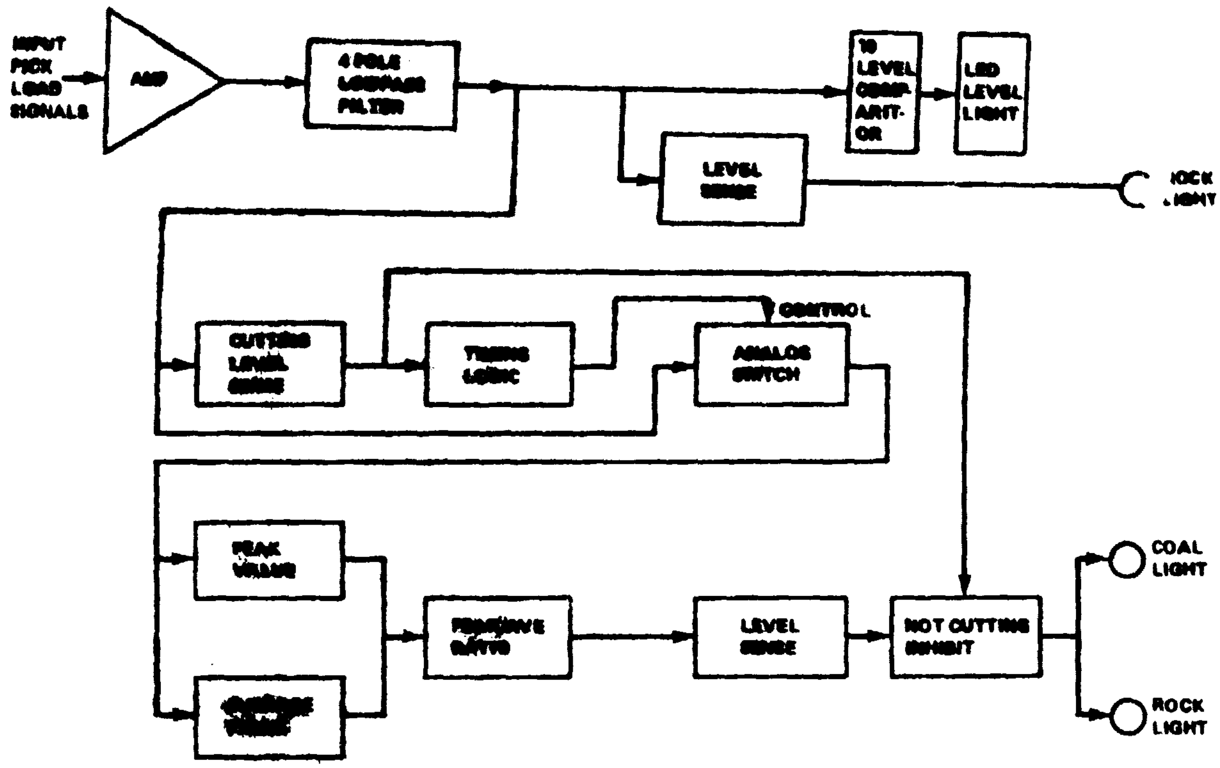


Figure 3-18. Pick load processor block diagram.

quotient of this ratio remains approximately the same. When the pick enters the rock, the signal level will increase for a small portion of the cutting period. The effect of this initial increase in signal level was found to be small in terms of the average value, but the relatively high-speed peak detector senses it immediately, increasing the value of the quotient which is detected by the comparator. Thus, a red light will flash on and off when cutting rock. During coal-cutting, a green light will flash on and off.

The pick detection circuit was designed to decay exponentially so that, when the cutting drum leaves the region of rock, the high peak levels will rapidly fall to the level of peak signal for coal. When the pick is not cutting, the peak circuit's inputs are disconnected, and the average value circuit holds its last value.

This is accomplished by disconnecting the input and feedback resistors from the circuit by solid-state switches. The switches were controlled by sensing the level of the signal. When the picks are not cutting, the signal level drops below the threshold level, causing the solid state switches to open. In the peak-average signal ratio, if the denominator of the ratio (average signal strength) is smaller than the numerator (the peak signal strength), the quotient is large. To control this value within the limits, an offset was designed into the denominator. A timing diagram of the switching logic is shown in **Figure 3-19. Figure 3-19A** illustrates the setting of the noncutting level sensor comparator above the normal level of noise, so that the level of noise lies below the trigger level. If the cutters are moving in a direction such that cutting starts at the roof, the signal will be high for the first half

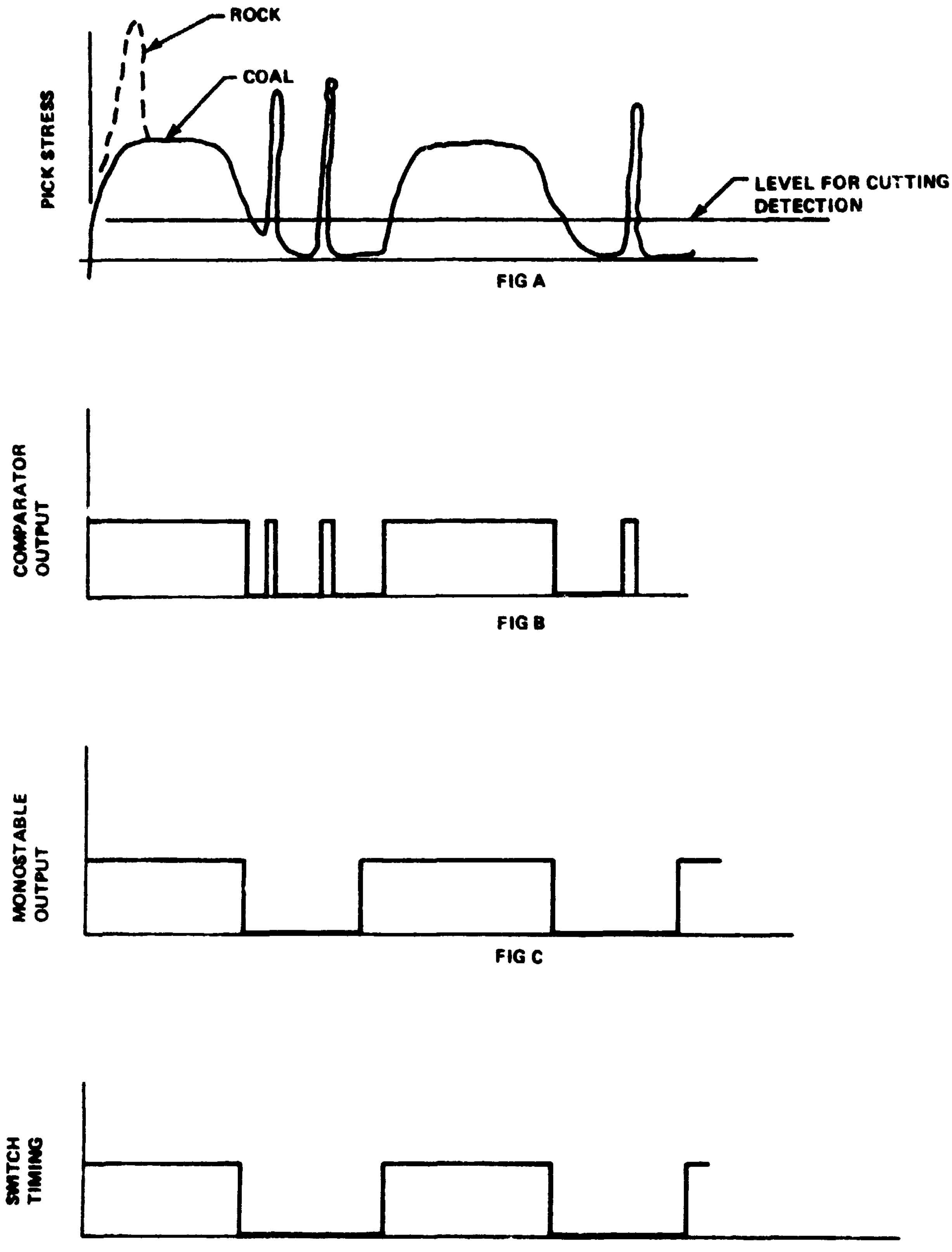


Figure 3-19. Sensitized pick timing diagram.

of a revolution. It is only during this period that the peak and average values of signal strength will be calculated.

The comparator transition from "on-to-off" was used to activate a retriggerable, monostable multi-vibrator which changes state. This "changed state" condition is timed for a little less than one-half of a revolution of the cutting drum, at which point it returns to its original state. These operations are illustrated in Figure 3-19C. When a logic "AND" is performed on signals represented in Figures 3-19B and 3-19C, false rock signals are eliminated as shown in Figure 3-19D. The detection method is designed to accept data for rock sensing in the floor or roof when the shearer is tramming in either direction.

There are four outputs from the signal processor:

1. Analog Output of low pass (100 Hz) filter (maximum voltage - 14 V)
2. Analog Ratio of peak to average value (maximum voltage - 14 V)
3. Digital Simple amplitude level detection (presence of rock - high level)
4. Digital Level detection ratio (presence of rock - high level).

General Design Considerations

All circuits were designed to be intrinsically safe using Underwriter Laboratories standard UL-913, dated January 20, 1976, revised on April 8, 1976.

Power to operate the signal processor is provided by twenty-four 1.4-V mercury batteries. Total voltage provided (using a margin of safety) is

$$(1.4 \times 24 \times 1.1) \times 1.25 = 46.2 \text{ V} \quad .$$

All batteries have current-limiting resistances connected at the battery terminals.

The LED's and the comparator have separate power supplies, provided by five 1.4-V mercury batteries. This provision prevents "on-off" surges from interfering with signal processing. The power required is 9.6 V.

The current limit for the signal processing batteries, based on MSHA requirements, is 0.3 A. The limiting resistance is therefore 154 Ω, which is obtained by using four 39 Ω resistors. The power dissipated in each resistor is 5 W. With a 100 percent safety factor, 10-W resistors were selected for use.

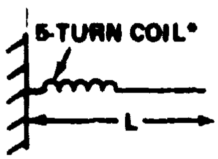
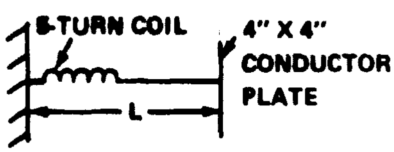
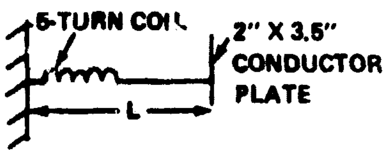
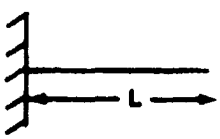
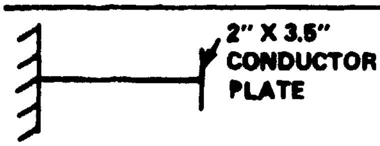
No current-limiting devices were required by MSHA for the LED batteries; however, a value of 0.5 A was used. The limiting resistance will be 19.2 Ω, which is achieved by using two 10 Ω resistors, with a power requirement of 2.5 W. For a 100 percent safety factor, 5-W resistors were used. All resistors will be either wire wound or of the metal film type.

Maximum capacitance values were also based on MSHA requirements, which dictated a maximum allowable value of 3 μf. Therefore, the voltage ratings of the capacitor should be 53.46 V.

The Antenna

The critical links in data transmission are the transmitter and receiver antennae. The operating environment of the sensitized pick places severe restraints upon antenna design, which forces a compromise between better radiating efficiency and structural ruggedness. Several configurations (Table 3-2) were investigated, and an interim selection was made using a straight wire (1.5-in. length) coupled at one end to a 4-1/4 by 2-1/4 in. copper plate. This configuration was expected to produce a

TABLE 3-2. ANTENNA OUTPUT OF VARIOUS CONFIGURATIONS

	Length of L (in.)										
Configuration	9.5	8.5	7.5	6.5	5.5	4.5	3.5	2.5	1.5	1.0	0.5
	180	170	130	110	90	65	50	35	–	–	-
	1000	330	250	250	300	350	400	200	–	–	–
	500	500	370	400	350	330	300	200	–	–	-
	–	–	–	–	55	45	38	25	15	8	7
	–	–	–	–	450	300	330	180	200	130	75
	–	–	–	–	300	150	145	180	180	100	85

*The 5-coil inductor is made of gauge 14 copper wire and the coil has a diameter of approximately 2.5 in.

reasonable field strength but short enough for ruggedness. One model was fabricated by placing a 1-1/2-in. thick HERKULITE spacer block between the aluminum transmitter housing and the copper plate, which was, in turn, covered by a 1/4-in. thick HERKULITE plate. This assembly was then bolted on the front face of the transmitter housing. In testing this assembly, a 39-1/2 in. receiving antenna was placed at 15 ft from the transmitting antenna, and a 100 μV output from the receiving antenna was measured. To enhance this output voltage, a 10-in. flexible, insulated conducting wire was soldered to the copper plate and glued to the HERKULITE cover plate. The test was rerun under the same conditions as before, and a 600 μV output was measured. However, the basic configuration without the 10-in. wire was tested at the Department of Energy's Bruceton test facility to determine field strengths at the receiving antenna for various transmitting locations around the perimeter of the cutting drum (Table 3-3).

TABLE 3-3. AF SIGNAL STRENGTH FOR VARIOUS DRUM PHASE LOCATIONS
(Clockwise Rotation)
(Bruceton Mock Longwall Data)

Phase Locations (degrees)	RF Signal Strength (μV)
0	250
45	150
90	120
135	50
180	100
224	140
270	210
315	210

In this series of tests, the receiving antenna was located at the midsection of the shearer body, which was considered to be the location of the receiving antenna during in-mine testing on an operating longwall shearer. The tabulated data shows that the field strength varied from 250 μV at the top position of the drum to 50 μV as the transmitting point approached 135 degrees. Because of this wide variation in field strength, a more reliable and stronger transmitting antenna was necessary. The configuration selected was a quarter wave length loop antenna mounted on the drum surface between the vanes (Fig. 3-16). Initial laboratory tests indicated a marked improvement in signal strength. Tests were then conducted on DOE's Joy machine at Bruceton, and RF field strengths of 800 μV to 4000 μV were measured. In addition, field strength measurements using the Eickhoff shearer in the York Canyon mine were made (Fig. 3-20). The introduction of the loop antenna improved the RF field strength by a 16-fold increase over the performance of the initial antenna configuration. In addition to the good transmission qualities of the loop antenna, it is structurally rugged; and that, together with its location, increases its survivability in the severe cutting environment.

In addition to changing the antenna itself, the tuning box was relocated to the backside of the pick mounting block. This location makes it more readily accessible for repair and maintenance (Fig. 3-21).

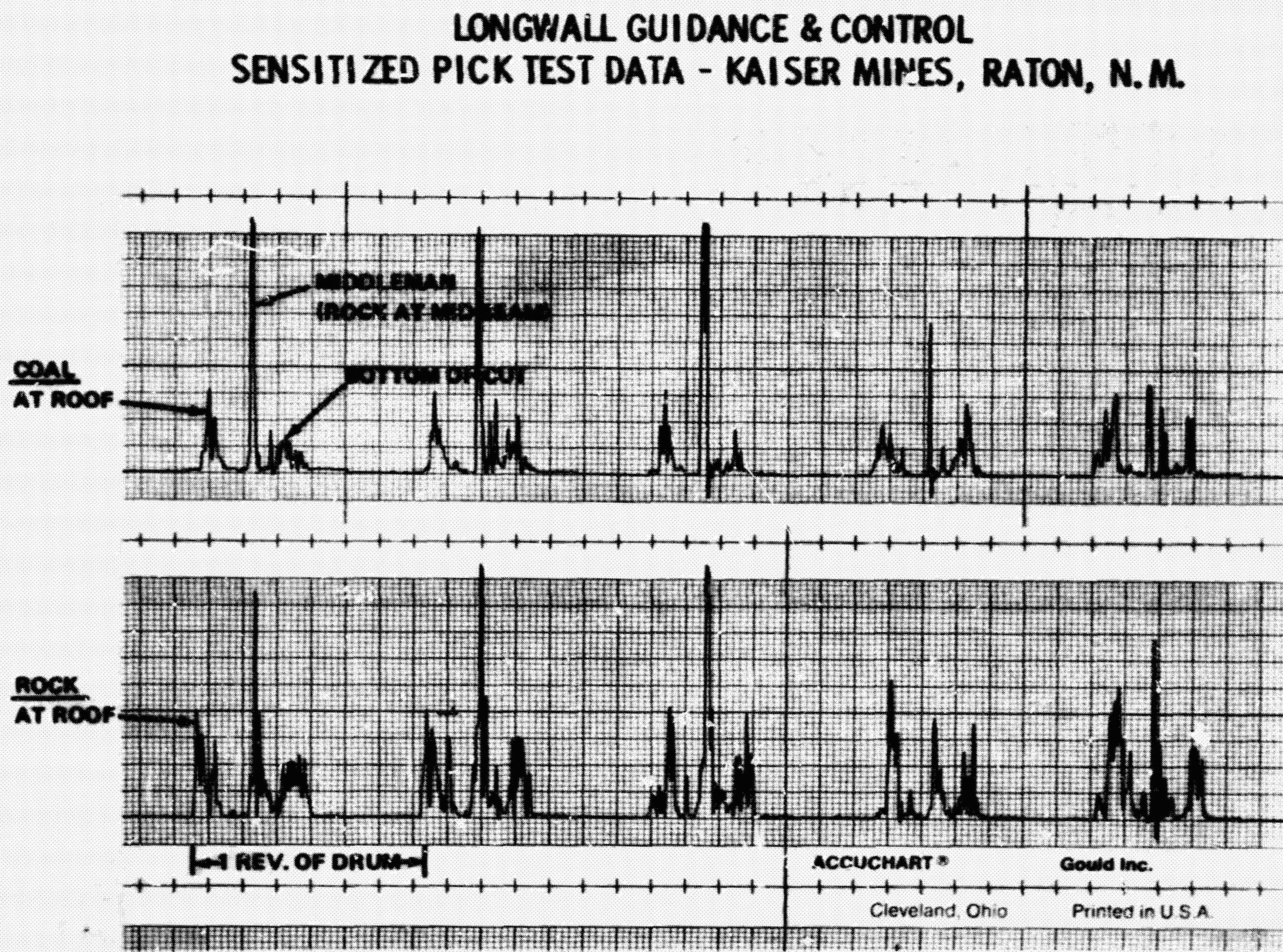


Figure 3 20. Kaiser Mine – sensitized pick signals.

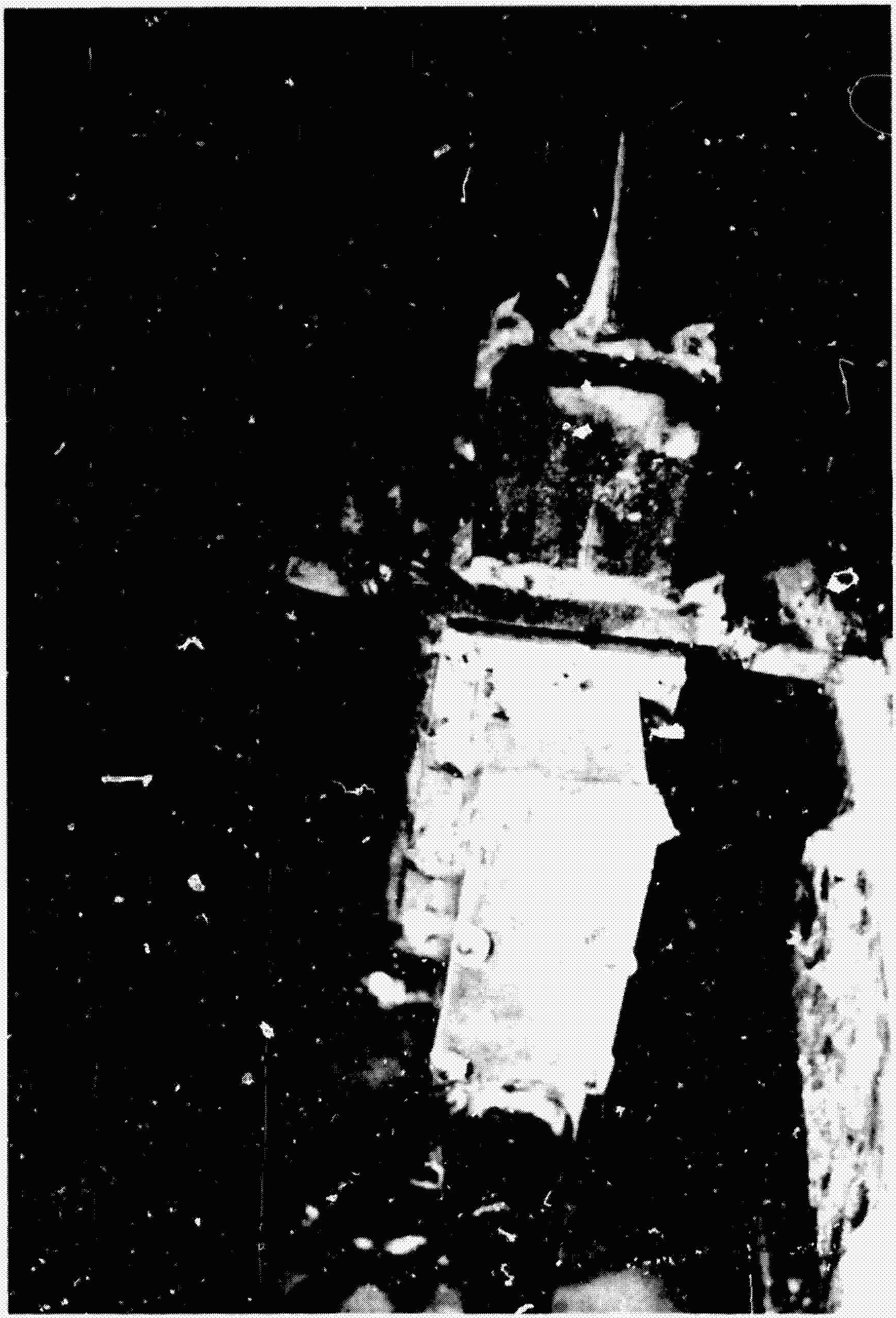


Figure 3-21. Sensitized pick mounted on a drum.

Above-Ground Testing

The above-ground tests were conducted at the Department of Energy's mock longwall facility at Bruceton, Pennsylvania, using a Joy longwall shearer equipped with a rack and pinion drive. The tests were planned to determine the ability of the sensitized pick to distinguish the cutting of the harder cap material from the less hard simulated coal in the simulated coal block. Other, secondary objectives were location of equipment on the shearer and experience in attaching the equipment to the machine. This latter objective culminated in a procedure that facilitated preparatory work in the very limited time available for attachment and checkout in an actual mine.

Above-ground tests were initiated in September 1980 and were repeated intermittently through April 1980. This series of tests identified several problems that interfered with the production and transmission of a reliable signal. Preloading the pick was observed to result in signal shifts as the preload relaxed during cutting. The preload was then reduced to a negligible value that no longer affected the signal. The receiver antenna was relocated from the midsection of the shearer body to the hinge point area of the shearer arm to reduce the signal path and insure a more reliable reception. The transmitting antenna was redesigned to increase the field strength and improve signal transmission quality.

All of these changes were incorporated; and in April 1980, a final Bruceton test was conducted to make sure that the instrument was performing properly and that its chances of being successfully tested in an operating coal mine were satisfactory. The test was judged satisfactory with the instrument successfully distinguishing simulated rock from simulated coal (Fig. 3-22).

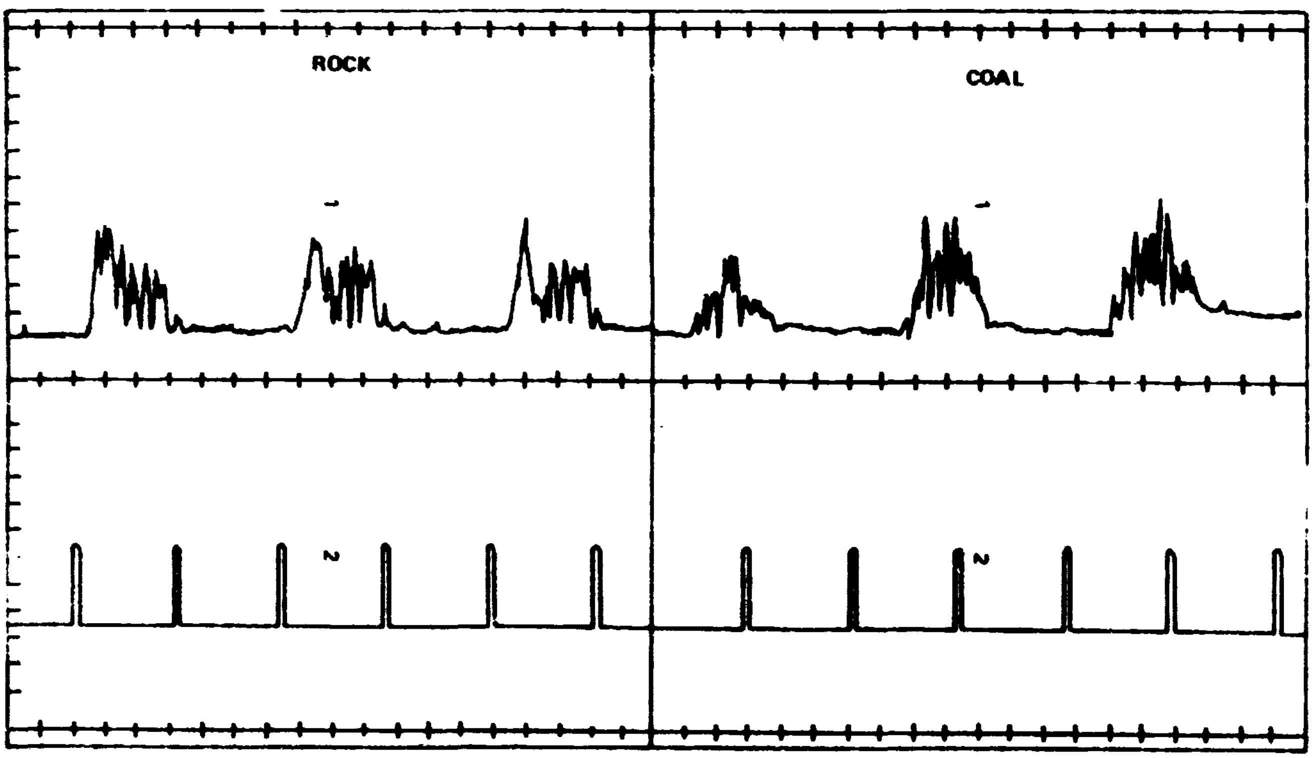


Figure 3-22. Typical coal and rock signals.

Mine Test of the Sensitized Pick

The sensitized pick was successfully tested at Kaiser's York Canyon Mine near Raton, New Mexico, from July 28 through July 31, 1980. Figure 3-21 shows the pick mounted between the two vanes, and welded to each as well as to the drum itself. The rod welded to the pick block at the bottom of the illustration, and extending back toward the reader, is the antenna. This mounting arrangement survived the environment of normal cutting; however, neither this configuration nor several standard mounting blocks were able to stand excessive cutting into a hard rock roof.

Figure 3-20 shows two cutting sequences: the top is where coal is being cut, the bottom where rock is being cut. Although it is not invariably the case, the leading edge of each pulse train, corresponding to the first engagement of the pick with the roof, was higher for rock than it was for coal. Extensive analysis of the amplitudes of the peaks shows that the use of the amplitudes as a discriminator gives the correct result approximately 70 percent of the time. Similar analysis of the initial slope of the wave form shows that the use of the slope (higher slopes correspond to rock) as a discriminator results in correct identification 70 to 75 percent of the time. Additional work was done in trying to find an additional discriminator, e.g., the integral of the wave form for the first 50 degrees or so. Unfortunately, the area of the curve seems to have little to do with the material being cut. The quest for a third discriminator was motivated by the desire to have a majority voting scheme: the material being struck is that which the majority of the discriminators agree that it is. In spite of extensive efforts, no third discriminator was found. However, using one of the two discriminators – maximum amplitude or maximum slope – is adequate for control purposes.

3.1.3 Nucleonic Coal Depth Sensor

The nucleonic sensor consisted of an active source of relatively low-level radiation directed into the coal layer and a receiver that picked up the radiation deflected from the coal/shale boundary. The thickness of coal was determined by the predictability of attenuation of the signal. Accuracy also required that both the transmitter and receiver be in contact with the surface of the coal. Initial test configurations consisted of a rigid rectangular frame housing the transmitter and receiver. However, the problems of "air gaps," those points at which the transmitter and/or receiver or both were not in roof contact, compromised accuracy. The air gaps were caused by irregular coal surfaces that were being measured. The final configuration, designed by Dr. Jones of Mississippi State University, consisted of a two-point contact, independently suspended unit (Fig. 3-23).

Initial tests of the two-point contact backscatter CID demonstrated the capability of measuring coal depth up to 10 in. when a 100 milli-curie Cesium-137 source is used and up to 6 in. when a 30 milli-curie source is used. Calibrations of the CID with 38-in. wide micarta sheets on a 6-in. thick concrete bed are shown in Figures 3-24 and 3-25.

Dynamic tests using micarta with 1-, 2-, 3-, and 5-in. depths are shown in Figure 3-26. The high peak in this figure occurred when the source module, which is leading, steps up to the next layer of micarta. The peak exists because there are many more scattered photons emerging from the material which reach the detector through the housing wall because of surface discontinuity. As the detector module moves toward the step, the count rate falls until just before the detector gains the same level as the module. This effect will occur when discontinuities in the surface to be measured are encountered, such as cavities caused by roof coal falls.

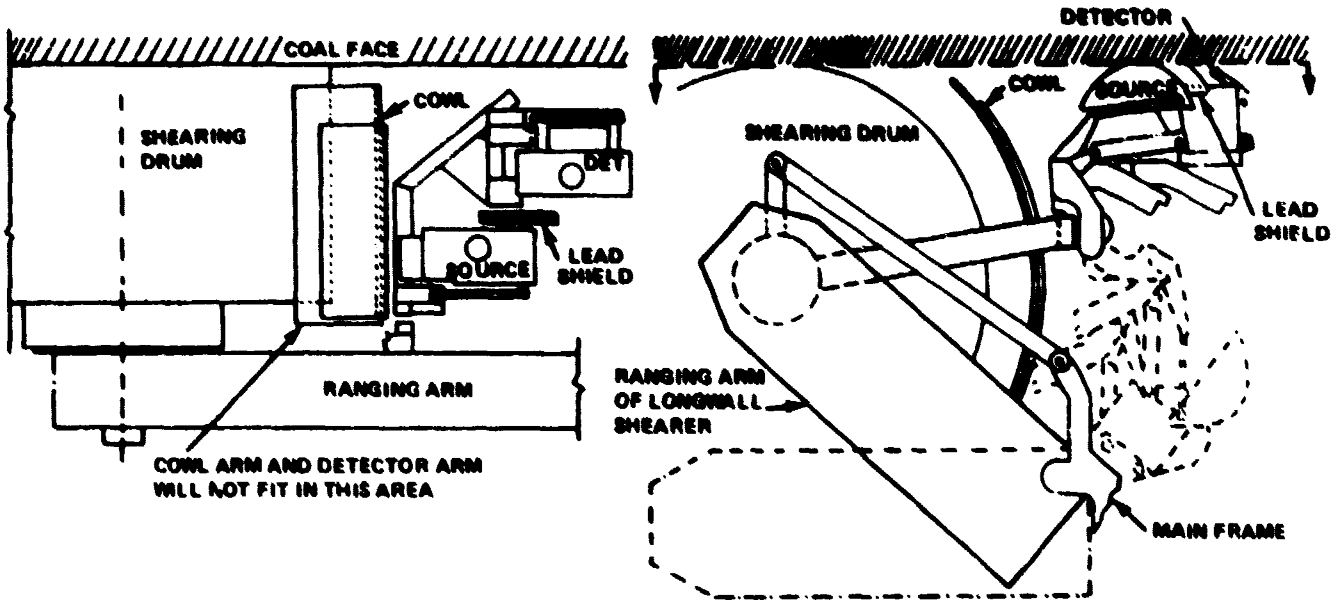


Figure 3-23. CID positioned on a shearer.

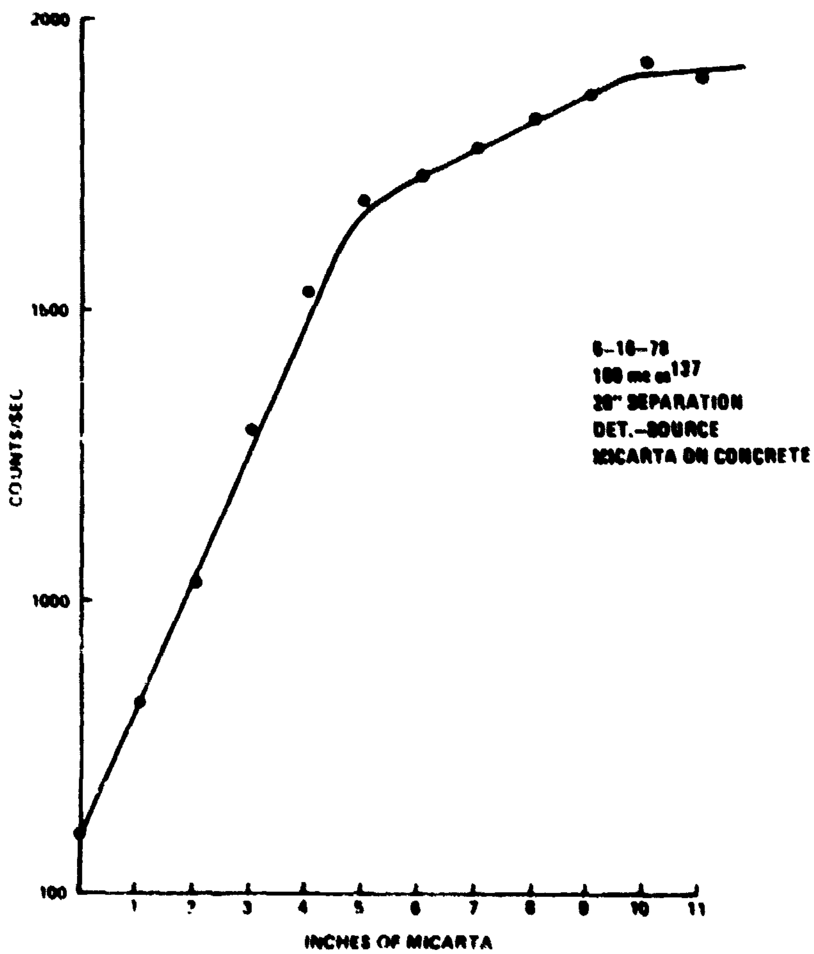


Figure 3-24. Backscatter CID calibration (100 mc cs^{137}).

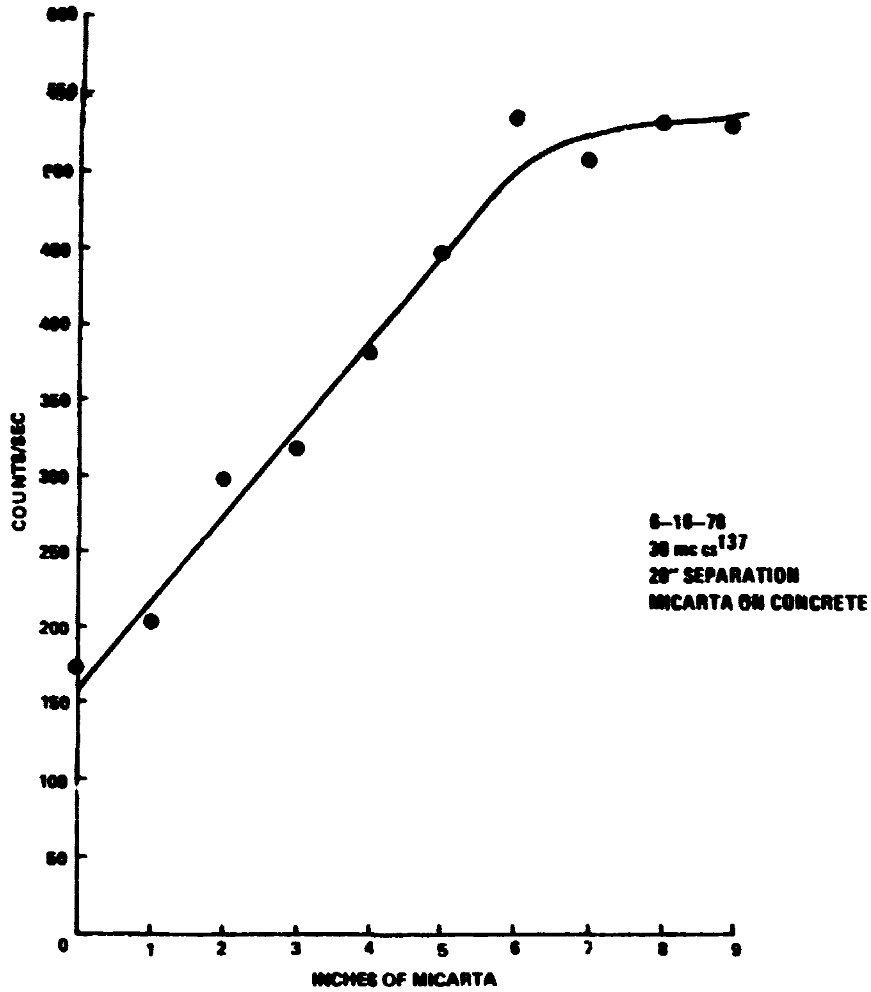


Figure 3-25. Backscatter CID calibration (30 mc cs^{137}).

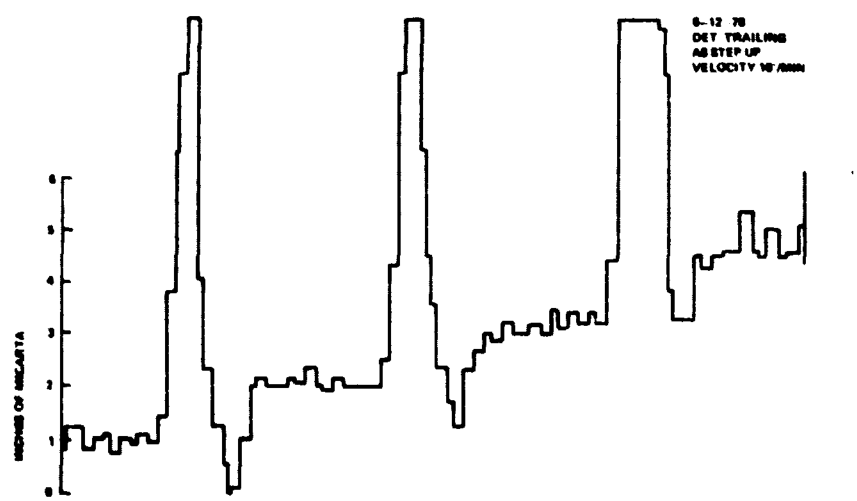


Figure 3-26. Dynamic output for CID on micarta.

Figure 3-27 shows the dynamic test results on a coal mosaic with depths of 2, 4, 6, and 8 in. Many of the hills and valleys in this figure are probably caused by voids or cracks between blocks of coal changing effective density and causing more or less signal attenuation.

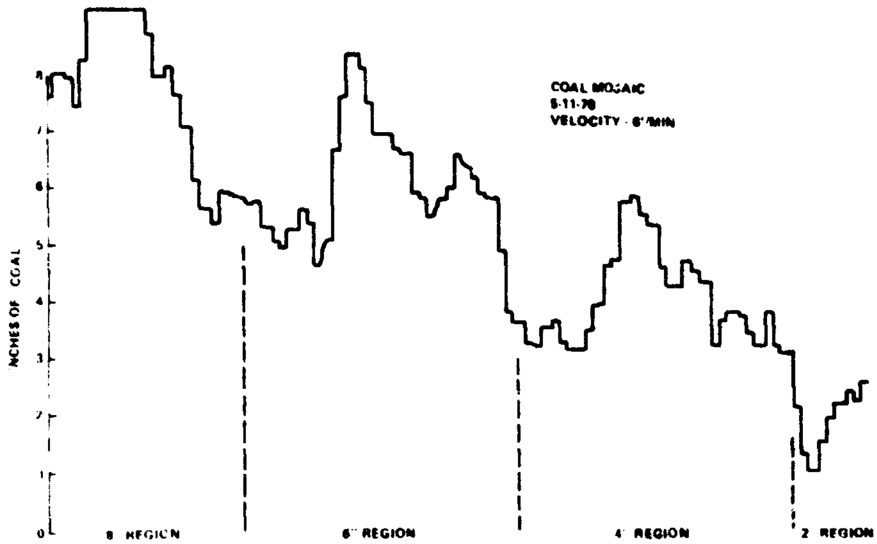


Figure 3-27. Dynamic output for CID on coal mosaic.

It is clear that the independently suspended module concept does maintain better contact with the surface and as shown by tests using the mosaic, the CID performance indicates that control over a ±2-in. depth is achievable. However, the presence of "air gaps" was still experienced during those tests which prompted a series of tests specifically to evaluate their effects upon accuracy. The results (Figs. 3-28 and 3-29) show the inaccuracies introduced in coal-depth measuring when a 1/4-in. air gap is present under the floating shield and detector (Fig. 3-28) and under the floating shield and the module containing the radioactive source (Fig. 3-29). In the first case (Fig. 3-28) with air gaps under the detector and floating shield, the mean value of equivalent inches measured is 7.2 in., or 1.2-in. deviation above the reference of 6 in. (about 20 percent). In the case of air gaps under the source and floating shield, the deviation is much greater. The mean value of the measurements recorded as 9.05 in., or 3.05-in. deviation above the reference measurement.

In-mine tests were conducted in BOM's experimental mine in Bruceton, Pennsylvania. The purposes of these tests were to evaluate in situ performance. The test plan was to measure the coal depth on a prepared surface consisting of a 2-in. coal layer 4 ft wide, a 4-in. coal layer 4 ft wide, and a 6-in. coal layer 4 ft wide; the position was undercut 40 in. The sensor assembly was mounted on a shop cart with 10-in. pneumatic wheels and a movable table top which could be raised 18 in. to position the sensor against the surface of the roof coal.

The actual prepared test cavity was measured; and the coal thicknesses found to be 5-1/2 in., 6-1/2 in., 9 in., and 10 to 11 in. Upon closer examination, the cut was found to slope downward from front to back so that the coal closer to the back of the undercut was thicker than at the front. The cut is shown in Figure 3-30. After initial tests were completed, the 5-1/2 in. coal was cut away with a pick to leave

CURVE	TEST CONFIGURATION	
	LINE CODE	CONDITION
A	SOLID LINE	¼ IN. AIR GAP UNDER DETECTOR & FLOATING SHIELD
B	BROKEN LINE	¼ IN. AIR GAP UNDER DETECTOR ONLY
C	DOTTED LINE	NO AIR GAP

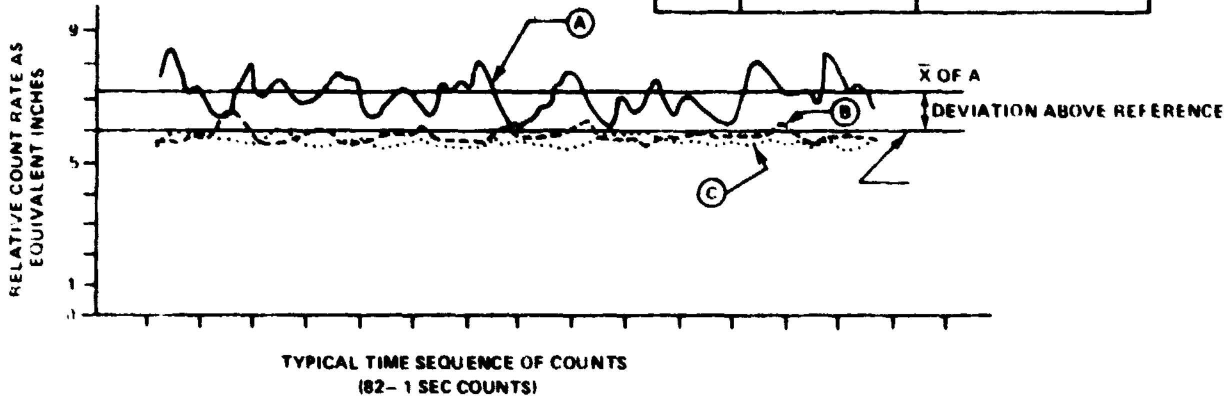


Figure 3-28. Backscatter CID – test results.

CURVE	TEST CONFIGURATIONS	
	LINE CODE	CONDITION
A	(SOLID LINE)	1/4 IN. AIRGAP UNDER SOURCE & FLOATING SHIELD
B	BROKEN LINE	1/4 IN. AIR GAP UNDER SOURCE ONLY
C	DOTTED LINE	NO AIR GAPS

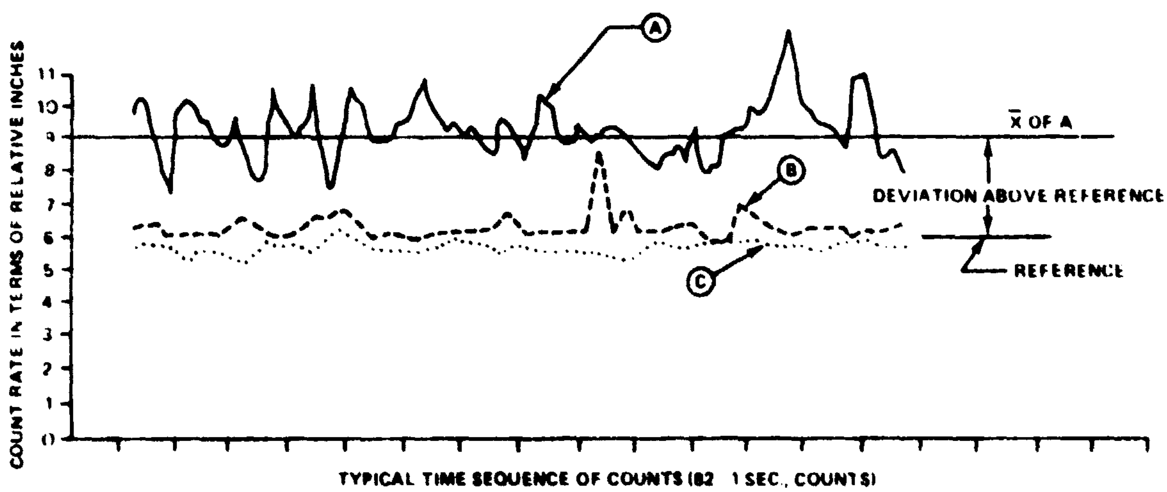


Figure 3-29. Backscatter CID – test results.

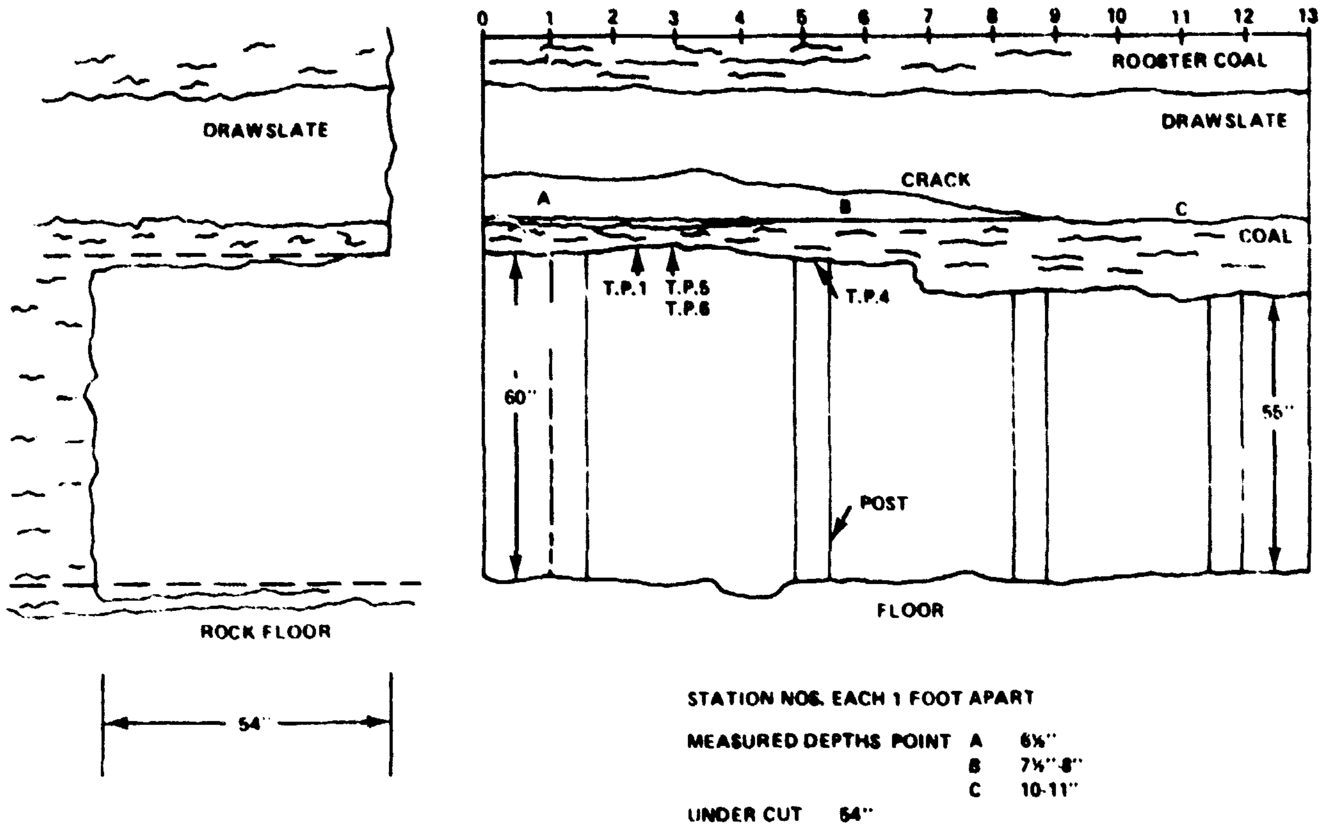


Figure 3-30. Backscatter CID – Bruceton test position.

about 1 1/2 to 2 in. of coal so that a measurement at that depth could be obtained, and finally all of the coal in the 5-1/2 in. step was removed to measure the values of the unattentuated signal.

In addition, the draw slate and coal cracks were observed running parallel to the surface of the cut, indicating a weakness that could lead to a roof fall if the supports were removed to provide room for maneuvering the cart. This condition imposed constrictions upon the locations at which measurements could be made from the three planned locations to only two, and in some cases one.

Representative data from these measurements are listed on Tables 3-4 and 3-5. By a visual inspection, the surface was observed to be rough and uneven so that air gaps were probable between the surface and the CID contact areas. In addition, the floor was not smooth and was not parallel to the roof, so the CID contact surfaces were never parallel to the cut surface; i.e., there was always a small angle between the contact surfaces for each measurement. It is known that the coal is more dense than micarta, so ideally the test data should lie below the calibration curve. As can be seen in Figures 3-28 and 3-29, they all lie above, a condition caused in part by

TABLE 3-4. NUCLEONIC CID – BRUCETON RAW DATA

Coal Thickness: 6-1/2 in. With Floating Shield						Without Floating Shield	
Test Position No. 1 (counts/sec)		Test Position No. 2 (counts/sec)		Test Position No. 3 (counts/sec)		Test Position No. 3 (counts/sec)	
1	497	1	512	1	470	1	492
2	464	2	448	2	472	2	498
3	498	3	506	3	460	3	546
4	490	4	472	4	491	4	516
5	496	5	535	5	505	5	511
6	453	6	474	6	465	6	494
7	458	7	497	7	491	7	534
8	507	8	485	8	505	8	519
9	516	9	492	9	517	9	495
10	486	10	524	10	455	10	496
	4865		4945		4831		5101
$\bar{X} = 486.5 \pm 21.3$		$\bar{X} = 494.5 \pm 26.1$		$\bar{X} = 483.1 \pm 21.5$		$\bar{X} = 510.1 \pm 18.7$	

TABLE 3-5. NUCLEONIC CID – BRUCETON RAW DATA

Coal Thickness: 7-1/2 to 8 in. With Floating Shield			
Test Position No. 4 (counts/sec)		Repeat (counts/sec)	
1	556	1	580
2	587	2	603
3	588	3	596
4	600	4	593
5	559	5	573
6	532	6	573
7	571	7	555
8	585	8	605
9	600	9	527
10	605	10	590
	5783		5795
$\bar{X} = 578.3 \pm 23.4$		$\bar{X} - 579.5 \pm 24.1$	

Note: Only one position available due to lack of room between roof supports. Crack in draw slate prevented relocation of roof support to allow move to different test position on this layer.

the contact angle and in part by surface roughness and the inaccuracies of measuring the actual coal depth. The bare rock had a surface that was relatively smooth and level, so that the angle of contact was minimal, and air gaps were less than 1/8 in. maximum. It appears that the rock may be less dense than the density of the concrete used for calibration. If this is the case, all data would be biased upward by approximately 50 counts in the range of 0 and 8 in.

Following a thorough assessment of development history, the nucleonic backscatter gauge, as a component of the vertical control system, was eliminated for the following reasons:

1) It required contact with the coal roof, which in turn required a mounting structure that protruded in the space above the shearer and was thus subjected not only to damage but interfered with the operation of the longwall shearer.

2) The use of a nuclear material, even though of a low radiation level, necessitated control procedures and possessed potential safety problems that made its use in underground coal mines complicated.

3) A less expensive and less complicated instrument t ι did not require roof contact, i.e., the natural background sensor, became available.

3.1.4 Electromagnetic (Radar) Coal Interface Detection

Of all the techniques investigated to measure the thickness of residual coal remaining after cutting the coal seam, electromagnetics (radar) appeared to be the most desirable. It was theoretically capable of making a measurement at a distance, and was not therefore in contact with the roof, and it could be mounted on the body of the machine by simple bracketry. A CW/FM and, to a lesser extent, a monocycle "pulse" radar were investigated. The CW/FM was investigated in 1 to 2, 1 to 4, and 2 to 4 GHz frequency ranges. In addition, a number of signal-processing techniques designed to make the echo from the shale interface electronically visible were incorporated into various configurations.

The basic problem, arising from the requirement of 2-in. target resolution, necessitated high frequencies, which in turn, buried the return signal in the front face return signal **(Fig. 3-31)**.

Several new RF signal processing techniques were developed. One, designed to translate the front face return signal into a DC spectrum component (sometimes called "Zero Hertz Filtering"), was successfully demonstrated and was incorporated into the signal process algorithm. Others, designed to reduce masking of the interface target signal caused by the front surface return signal, met with only partial success. However, a new concept of using the front surface signal as the local oscillator to eliminate one of the two surface signals (resultant signal represents the differential between front and rear) provided an improvement of 3 to 6 dB in target detection. Initial laboratory tests of the 1 to 2 GHz radar configurations were performed to assess the effect of incorporating various components to eliminate or reduce the "target masking" effect. Two linear antennae coupled to a YIG generator were assembled and tested using cement blocks as targets. Operating mode utilized the front surface local oscillator concept (FSLO). The radar was able to measure a cement block 20-cm thick with good signal to background noise ratio. About four cycles of data were obtained per sweep period, which would imply a minimum range of approximately 10 cm with accuracy of 5 cm.

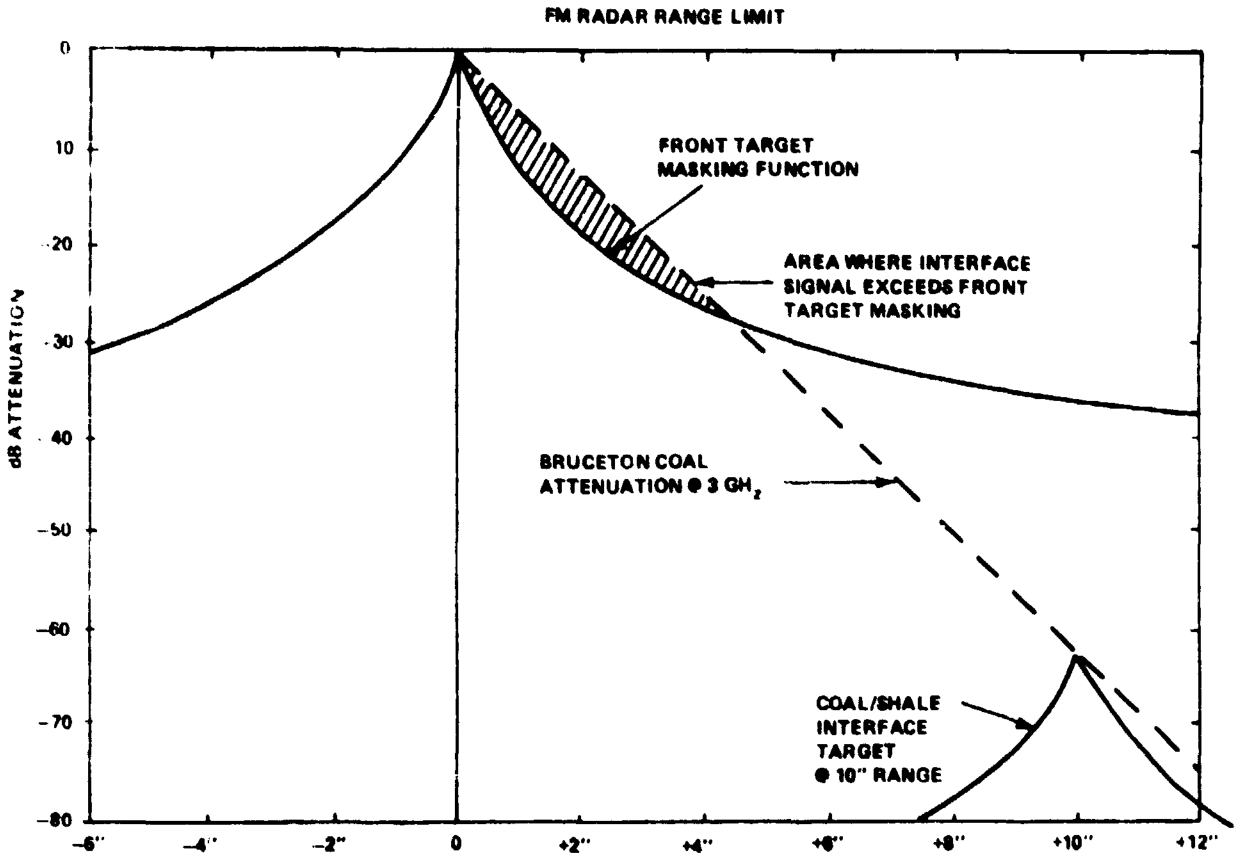


Figure 3-31. Radar range reference to front surface.

The following experiments on signal process algorithms beneficial in target detection were performed:

1) Averaging multiple sample signals from a moving radar was studied. This technique was found to provide a substantial reduction of the number of false targets and to materially increase the probability of true target location. Four to six samples were found to be required for clear target detection. Sample test results using the signal processing techniques are shown on Table 3-6.

2) Using a technique in which pre-bandpass filtering of radar data to expected target frequency location before A/D conversion was investigated. For the case of a 1 to 4 GHz system being swept at 100 Hz, a limit was found at 300 to 1800 Hz.

3) Introducing zero hertz filtering, the process of isolation of the front target by limiting the amplitude, filtering, and heterodyning with the weaker rear (coal/shale) signal to translate to a low frequency differences signal, was also investigated.

4) Using sampling windows for discrete Fourier Transforms is multiplication of a time domain input function by a window function which is necessary to obtain a clear separation of two frequencies in a small range of frequency differences (such as front and rear targets). Both the "Hanning" and "Blackman-Harris" windows were tried. The "Blackman-Harris" window appeared to give better results (target separation).

TABLE 3-6. RESULTS OF LABORATORY TESTS (RADAR)

Target Type	Target Dimensions	Radar Measurement (cm)
Cinder Block	25 cm	26.1 24.4 22.7 26.1 26.1
Coal	6 cm	5.2 5.2 5.2 5.2 5.5
Coal	12.5	12.3 12.3 12.3 12.3 12.3

5) In addition, a 2 to 4 GHz CW/FM radar using the front surface local oscillator (FSLO) concept was successfully laboratory tested with two large coal samples of 6.5 and 12 cm in thickness. Radar movement and the use of power spectral density averaging of four samples were required for consistent results. Sample thicknesses were measured correctly approximately 80 percent of the time. The 12-cm coal sample required an aluminum foil backing for consistent target returns. The 6.5-cm thick coal block could be measured with and without foil backing. Both samples were old "dried-out" coal, and attenuation was a little less than for freshly cut coal.

The concept of using the reflected signal from the coal face as the local oscillator has proved to be beneficial. Experiments using this concept (FSLO) have shown marked improvement in detecting the weak interface with a minimum amount of masking from the strong front surface signal. The front surface signal is received, amplified, and detected using a conventional diode mixer. The mixing process produces a difference signal that is directly proportional to coal thickness. The front surface signal is used as the local or reference oscillator instead of obtaining this signal from a tap on the YIG output, as in previous designs. Zero hertz filtering was found to be no longer necessary. Initial tests indicate a 3- to 6-dB improvement over conventional FM/CW radars.

6) A Front Surface Local Oscillator Frequency Modulated (SLOFM) radar was constructed in an effort to simplify the radar measuring process and to improve the radar's ability to detect the weak signal from the coal/shale interface.

The conventional FM/CW radar used for coal thickness experiments (Fig. 3-32) consists of a modulation source (a 100 Hz triangular wave oscillator), which modulates a radio frequency oscillator (2 to 4 GHz). Energy from the RF oscillator is also fed to a balanced mixer. The signal emitted from the antenna travels to the coal and is partially reflected from the front surface back to a receiving antenna. The signal also passes through the coal and is reflected at the coal/shale interface back to the

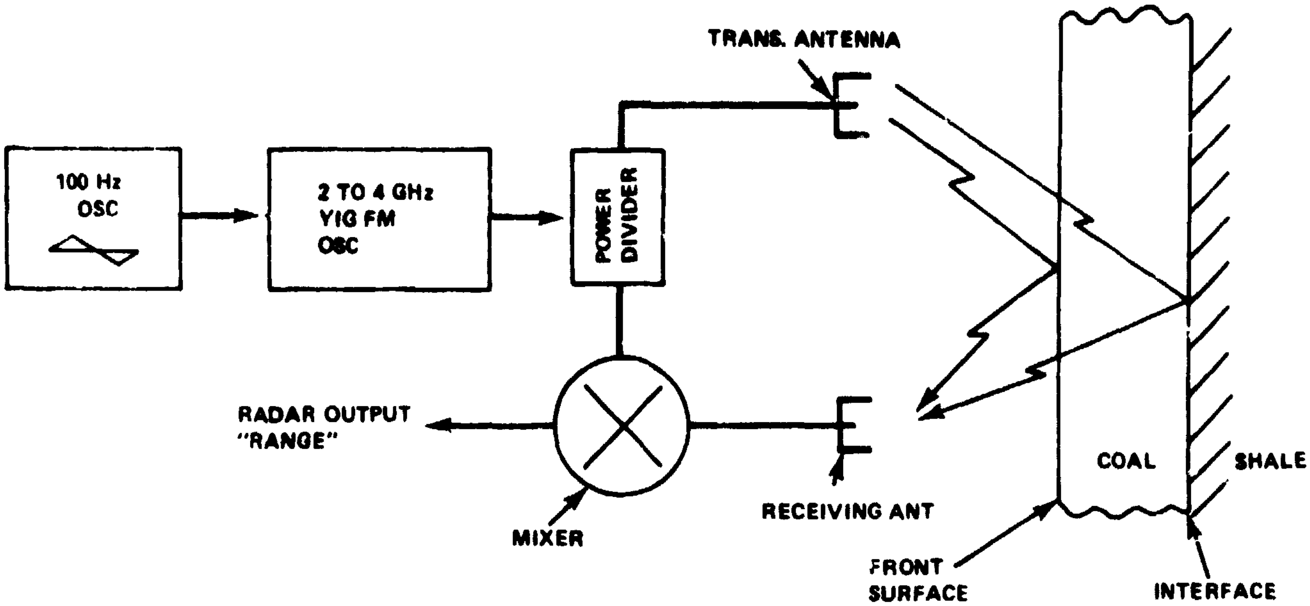


Figure 3-32. Conventional FM-CW radar.

receiving antenna. The receiving signals are then detected in the mixer. The mixer output will contain frequency components relating to distance from the radar to both front and rear (interface) coal surfaces.

The improvements incorporated in the FSLOFM configuration (Fig. 3-33) determine coal thickness by subtracting the front and rear (interface) ranges. Additionally, range is referenced to the mixer located within the radar. Since the local oscillator signal is obtained from the front coal surface, it will be mixed with the closest difference signal (in this case the rear coal shale interface). The difference in frequency thus is proportional to the coal thickness. This radar configuration embodies the following advantages over a conventional FM/CW system:

a) The coal thickness measurement is a direct output of the mixer and requires only a frequency-to-thickness conversion.

b) The masking effect from the front surface return is eliminated since the front surface is no longer detected.

c) Extraneous targets from electrical discontinuities of the transmitting antenna are removed. This is because no target information is generated until after the front coal surface return arrives at the mixer to perform the local oscillator function.

Additional laboratory tests to investigate the 2 to 4 GHz radar's ability to measure coal thickness and to read or print out the thickness in a teletype format were conducted. The test samples were 6.5- and 12.5-cm thick coal and a cinder block which was equivalent to 2.2 cm of coal. The radar performed well with correct readings approximately 70 percent of the time. The radar used in this test series was the so-called "Orange Radar" which has a teflon cover over the front. The cover causes coupling between the transmitting and receiving antennae, thus defeating the front surface local oscillator principle. Therefore, the cover was removed for the

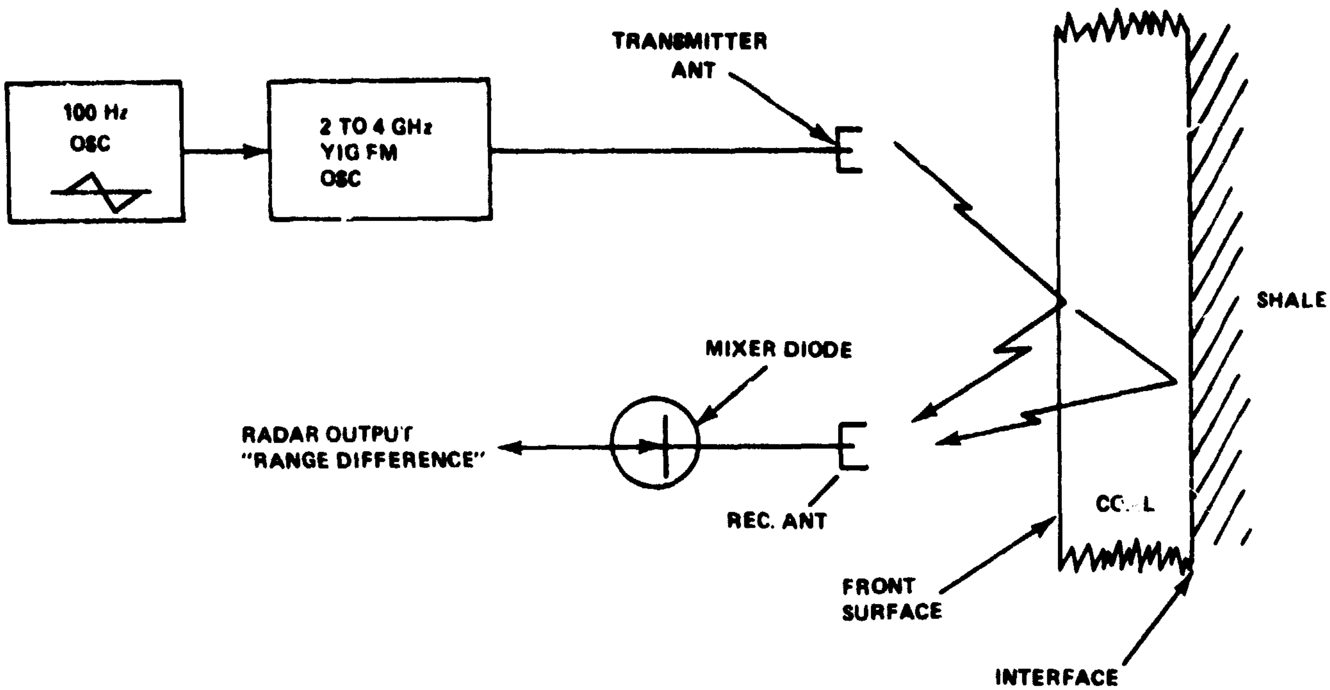


Figure 3-33. Front surface local oscillator.

above demonstrations and tests. The "Orange Radar," in its present enclosure, was considered marginal for the VCS application as a result of the coupling. A new enclosure was designed, using two separate antenna covers to eliminate or reduce the coupling.

However, when the radar was tested on the simulator using a coal mosaic as the target, the tests failed to produce reliable thickness measurements. The coal mosaic is made up of a "brick size" coal cemented together to form a slab in steps of 2-, 4-, 6-, and 8-in. thickness. This failure led to the search for a better and more representative target.

A contract was awarded to Emerson and Cummings to fabricate an artificial coal dielectric material with electrical characteristics equivalent to Bruceton mine coal which would provide a more realistic target for radar tests. Fresh samples of coal were obtained at Bruceton and measured at Emerson and Cummings for their electrical characteristics. The measurements were made at 3.0 and 8.6 GHz. Emerson and Cummings measurements are reasonably close to those measured at MSFC. (MSFC θ = 3.75 and the loss tangent = 0.071.)

The dielectric constant of a sample of shale from Bruceton was measured to be 8.9. This measurement will give a shale/coal dielectric ratio of 2 to 8 providing operation above the knee of the reflection curve (Fig. 3-34). The figure, taken from Von Hipple, represents the radar reflection versus dielectric ratio and signal attenuation in coal versus dielectric constant and loss tangent 3 GHz. The shaded area of Figure 3-35 represents the anticipated range of coal electrical characteristics to be encountered. Substantial effort was expended to develop a detailed analytical model of the coal radar. Particular emphasis was in understanding the target amplitude

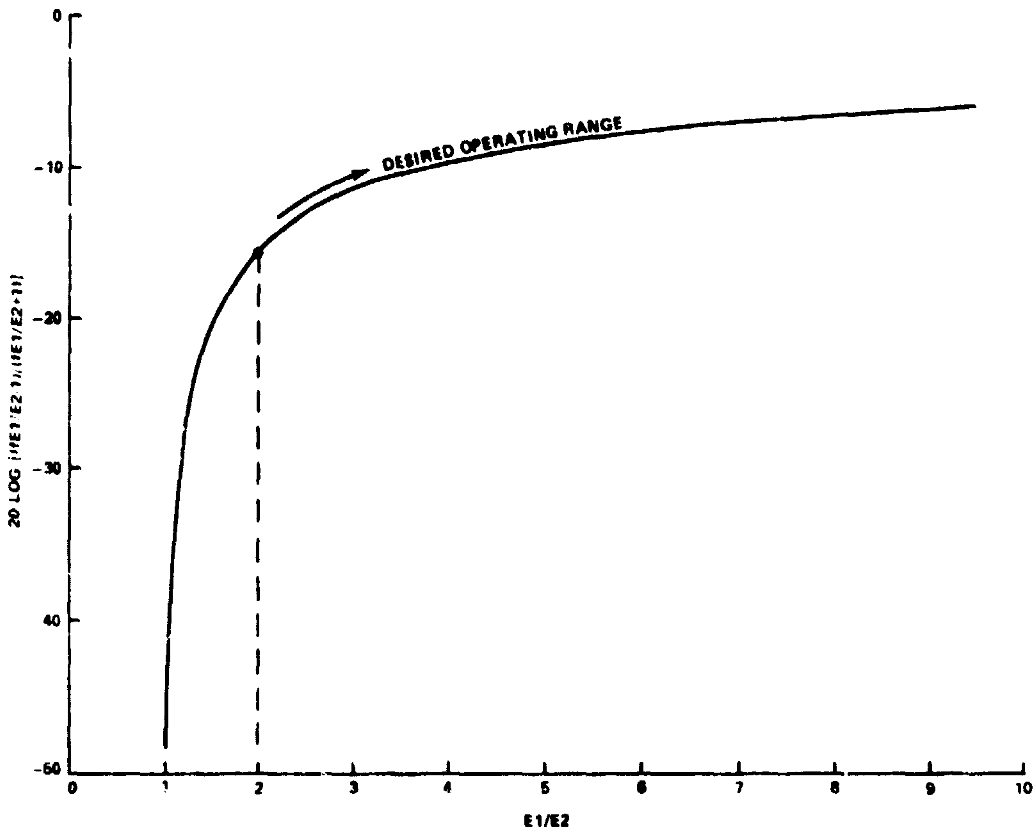


Figure 3-34. Dielectric ratio of shale/coal.

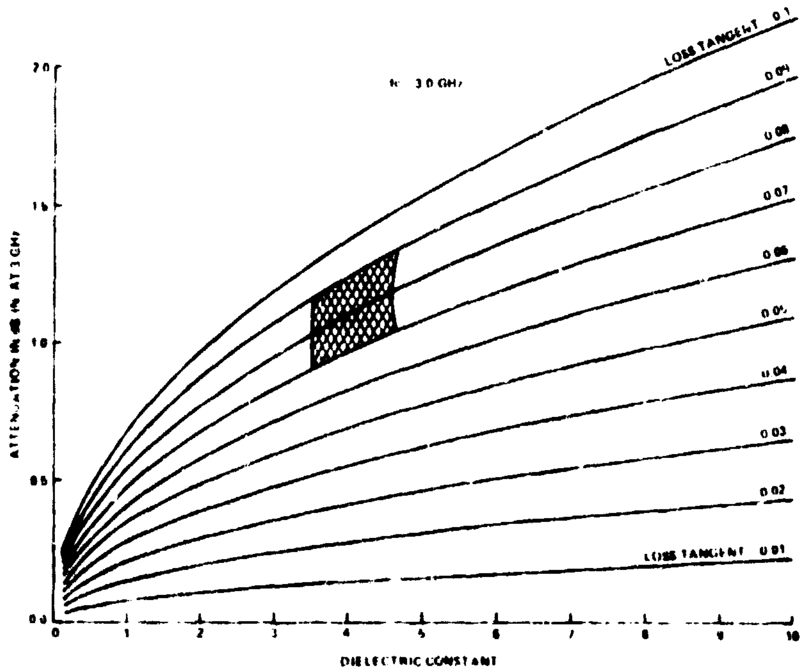


Figure 3-35. Attenuation versus dielectric constant for various loss tangents.

frequency distribution. A fundamental problem encountered in use of the Fourier transform of the demodulated return signal is that spectral lines lie at discrete multiples of the modulating frequency; whereas the frequency difference between the transmitted and reflected signals is not, in general, an exact multiple of the modulating frequency, and does not explicitly appear. Thus, a direct examination of the spectral distribution does not provide an accurate measure of the difference frequency, which contains the range information.

However, it has been shown that the spectral envelope of a periodically repeated sinusoidal time function is of the form sin x/x . The possibility of obtaining the value of the difference frequency by performing a correlation of the spectral line distribution with a sin x/x function appeared attractive and was investigated. The results indicate that this approach is effective in identifying the difference frequency for the simple model that was considered.

The next series of tests using the 1 to 2, 2 to 4, and 4 to 8 GHz radar configurations was conducted in the BOM Bruceton experimental coal mine. The signal detection used was the conventional method in which a portion of the transmitted signal is used as a local oscillator for the received signal, and the second method was baseband detection that depends on the front surface return to act as the mixing signal.

The test area in the mine was a cavity cut approximately 12 ft wide and 4 ft deep. The remaining coal on the roof of the cavity varied from approximately 3 to 11 in. in thickness. Each radar was moved under the roof by a cart on rails. Station locations were marked on the cavity to identify where measurements were being taken. The coal thickness at each location was measured and recorded. The output of the radars, along with station identification, was recorded for later analysis. The data was analyzed by processing 40 samples of the return to obtain one measurement. The error of the measurement was then determined using the actual measured thickness from the recorded station number. The mean error, RMS error, and standard deviation of the measurements were then plotted versus actual coal thickness. Figures 3-36 and 3-37 are selected from approximately 70 test runs as being representative of the best data. Figure 3-36 represents a test that is considered a failure. In the tests represented by Figure 3-37, the radar appears to be detecting the interface coal thicknesses less than 6 in. As can be seen by these figures, the error appears to vary linearly with coal thickness greater than 6 in. and to be constant for coal thickness less than 6 in. This indicates that something different (such as interface detection) is occurring for coal thickness less than 6 in.

The success of the radar to accurately measure coal thicknesses did not meet expectations.

However, long-term future research-type investigations of FM/CW radar may proceed along the following lines:

1) Development of a method for determining the thickness of a layer of coal by computing the difference between a frequency associated with the front surface of the coal layer and a second frequency associated with the rear surface.

2) Identification and characterization of various extraneous signals which corrupt the information-bearing signal and which degrade the accuracy of the frequency-difference computation.

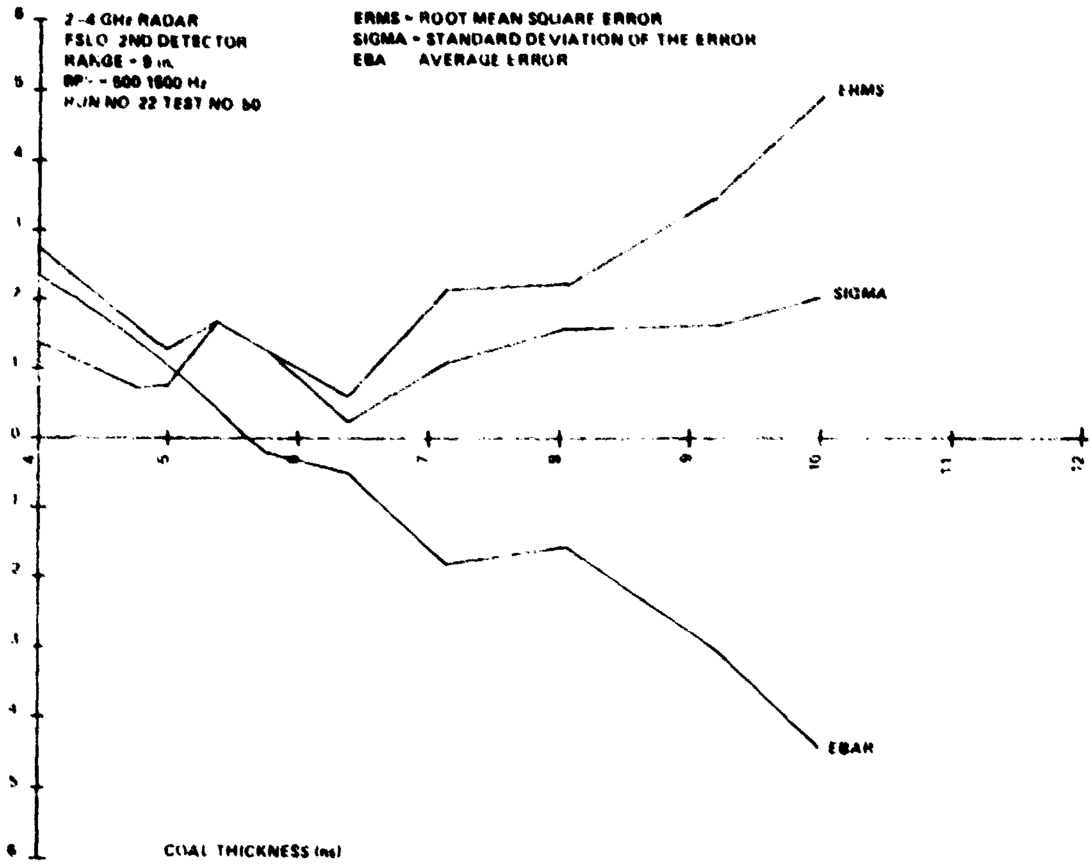


Figure 3-36. The error in range measurements (radar).

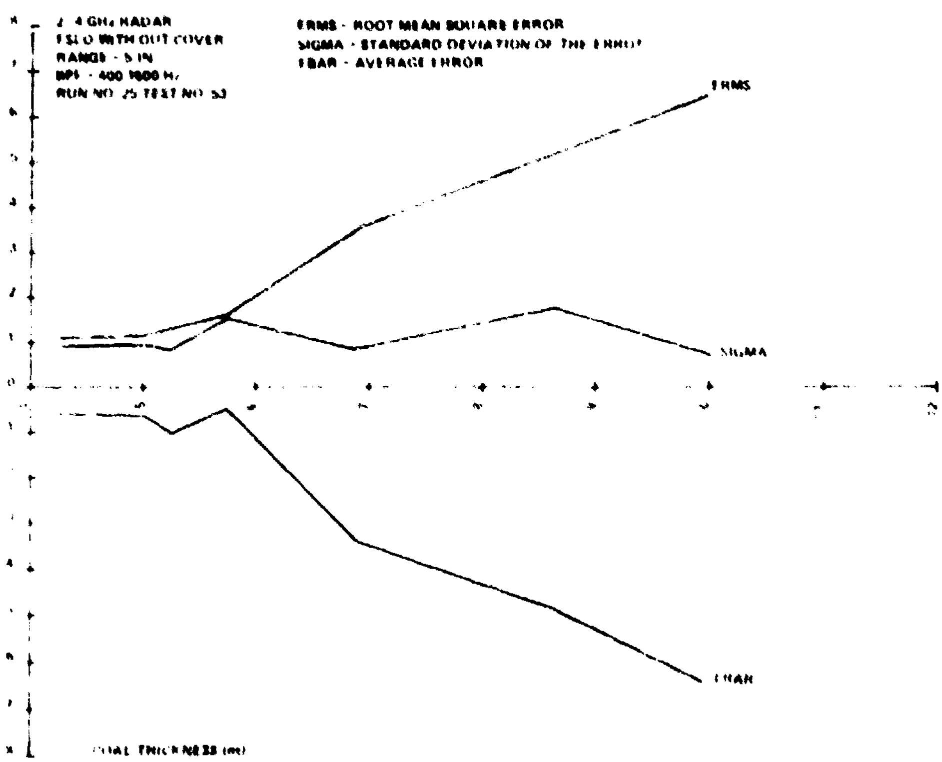


Figure 3-37. The error in range measurements (radar).

3) Investigation methods for minimizing the detrimental effects of the interfering signals.

Five facts regarding the return signal from the radar should be recognized:

1) The frequencies associated with the front-surface and the rear-surface returns do not explicitly appear in the spectrum of the return signal. Rather, their energies are divided among the harmonics of the modulation frequency, except in certain special cases.

2) The return signal from the rear surface of the coal layer, for the maximum thickness to be measured, is very weak in comparison to the signal reflected from the front surface.

3) Electrical discontinuities, produced by various junctions in the signal flow paths of the system, produce reflections of the same type as those produced by the coal surfaces. These spurious reflections tend to obscure information-bearing signals reflected from the coal surfaces, particularly those from the rear surface.

4) Multiple transmission paths in the space surrounding the radar also contributed spurious frequencies and tended to degrade the measurements.

5) Imperfections in the performance of the system components, such as the oscillator and the mixer, further corrupted the output signal and obscured the desired information.

The net result of these conditions was a composite output signal in which the information-bearing one is low amplitude and must be extracted from a mixture of contributing signals. It must then be processed to reveal the desired information.

In that regard, the following paragraphs sum up the observations and experience gained during the radar investigations.

Frequency-Difference Computation: The nature of the spectral distribution of the harmonic frequencies makes direct observation of the front-surface and rear-surface return frequencies impractical. Therefore, it is evident that the composite output signal must be processed in some way to derive the desired difference between the front-surface and rear-surface frequencies; hence, the thickness of the coal layer. A mathematical process for performing this function was devised. The process involves the use of the magnitude of ten sequential harmonic frequencies in the spectrum of the output signal. These Fourier coefficients consist of five simultaneous linear equations having five unknowns. The set of equations is then solved for two of the unknown quantities; and from these two quantities, the differences between the front surface and rear surface frequencies are computed. It is assumed that all interfering signals have been sufficiently suppressed to permit an accurate solution. A Fortran program for performing the computations has been written, and a large number of test cases have successfully run on a simulation model.

A Fortran program was used to perform the calculations since this provides flexibility, and the computer is readily available. Should this data processing be committed to hardware, it could easily be implemented using an off-the-shelf microprocessor on a printed circuit card approximately 8 by 10 in.

Characterization and Suppression of Interference Sources: Characterization of the spurious signal sources and methods for reducing their effects was investigated. Impedance mismatches which produce a voltage standing wave ratio (VSWR) as low as 1:1:1 produce intolerably high reflections. It is clearly impractical to appreciably reduce these discontinuities below that value. It is fortunate, however, that their effects may be essentially eliminated by suitable choices of line lengths which place the frequencies of the interfering reflections outside the information passband. A test configuration using coaxial cables to simulate the transmission paths to and through the coal was constructed and proved very useful in identifying, characterizing, and eliminating sources of spurious signals in the system. Effects of various impedance discontinuities, nonlinearities in the YIG oscillator, and undesirable effects in the mixer were isolated and studied.

A monocycle radar was fabricated using available components and tested using coal dielectric material received from Emerson and Cummings as the target material. Figure 3-38 is a block diagram of the equipment. The impulse generator produces an impulse with a 70-picosecond rise time and a 200-picosecond fall time. This impulse was then fed to a horn antenna with a pass band of 2 to 6 GHz. The receiver was another horn antenna, using a sampling oscilloscope as a receiver and detector. Figure 3-39 is a recording of the signal. The first trace is the analog return signal as detected by the oscilloscope. The first set of "wiggles" is a result of the front surface reflection, and the second set of "wiggles" is due to the coal/block interface. In this case, a 1/4-in. air gap was introduced to emphasize the interface. The second trace is a correlation between the front surface reflection and the entire reflection. The third trace is correlation rectified, and the last trace was produced by filtering the rectified correlation. The interface is easily identifiable. This is not an accurate simulation because of the air gap. Figure 3-40 is the same experiment repeated with no air gap. Identification of the coal/block interface is now questionable. This also is not accurate since the contrast ratio between coal and cement is worse than that of coal shale.

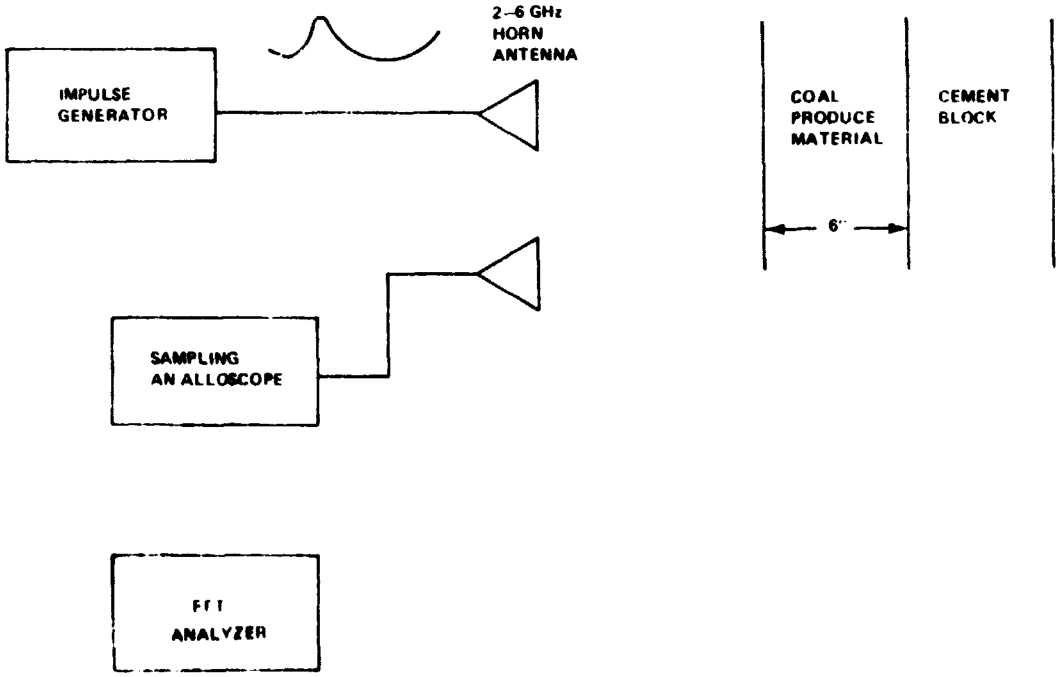


Figure 3-38. Schematic of arc impulse radar.

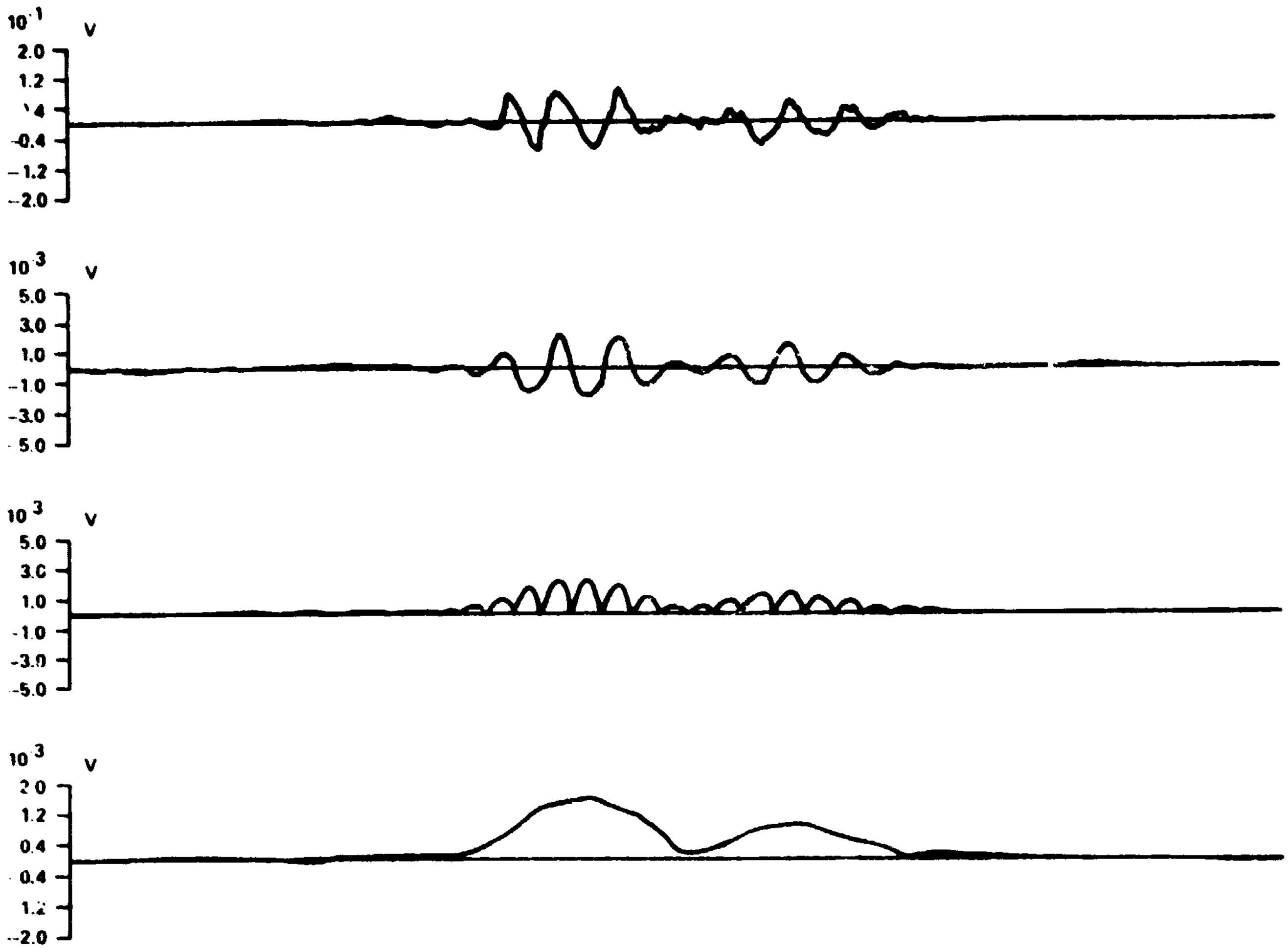


Figure 3-39. Signals (impulse radar experiment).

The results, while promising, did not offer a marked improvement over the FM/CW configuration. This effort was terminated, along with that on FM/CW radars, in view of the more promising and less expensive natural background coal thickness sensor.

3.1.5 Magnetic Spin Resonance

Investigations structured to evaluate the use of the principles of magnetic spin resonance (see item 2 of the appendix) to residual coal thickness measurements were conducted at Southwest Research Institute under provisions of Contract NAS8-32606.

Initial studies in the laboratory established the fact that coal and shale samples, inserted into the core of a radio frequency coil which in turn was suspended between magnetic poles, produced distinctive amplitude signatures and thus formed the basis for coal-rock discrimination. The problem faced by Southwest Research was to demonstrate that the same discriminatory measurement could be made in a magnetic field outside the core of the coil and at some distance above the instrument.

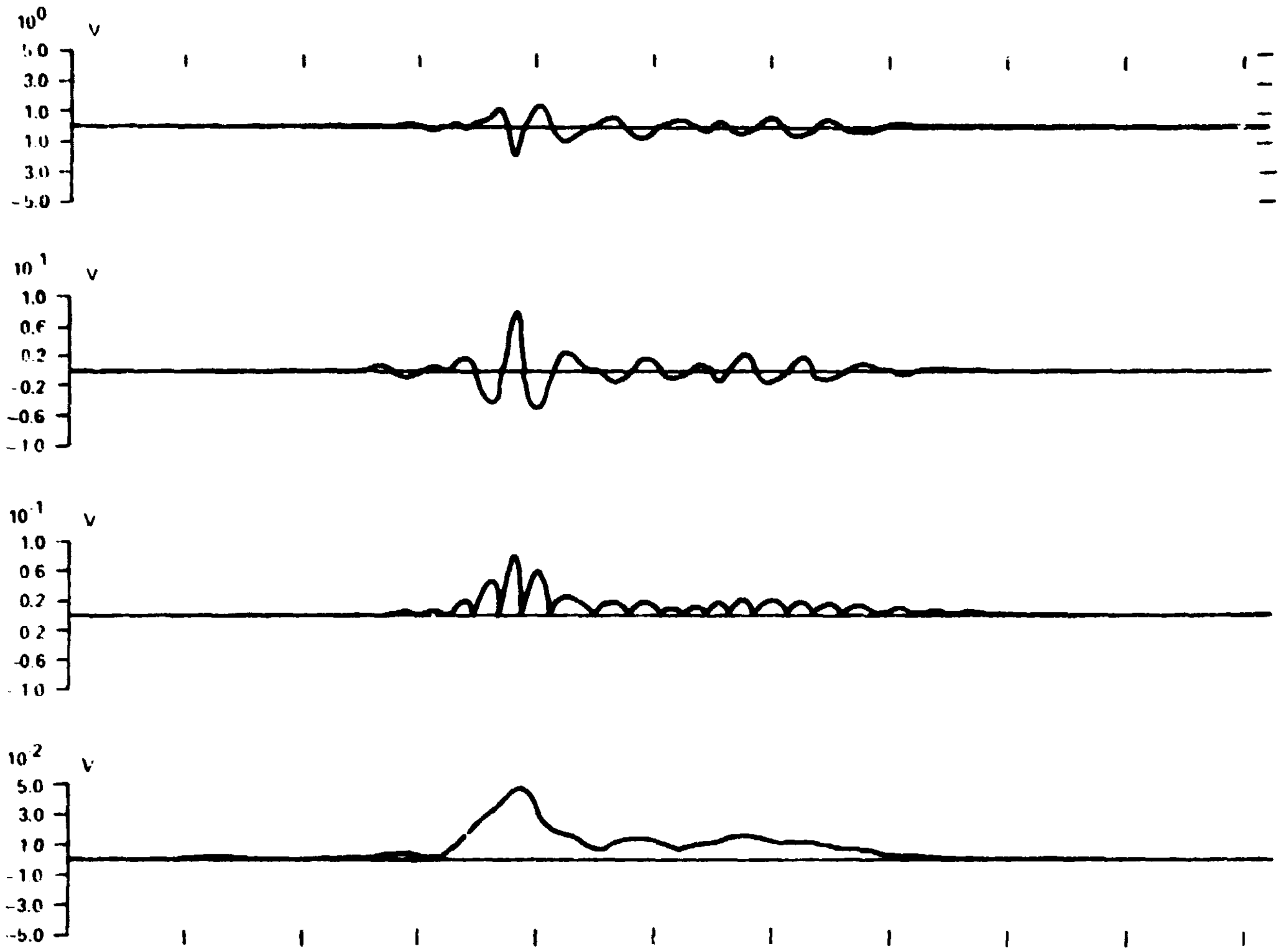


Figure 3-40. Signals (impulse radar experiment) no airgaps.

Initially, a mathematical model was devised that permitted evaluation of parameters influencing the measurement and allowed an ordered approach to hardware design considerations. Specifically, the model relates range, resolution, and sensitivity variations with distance and provides the capability of evaluating these parameters. Applied to the apparatus described above, the magnetic field produces a bias field, H_o. The RF coil is used with an appropriate transmitter, receiver, and auxiliary apparatus to detect electron magnetic response from the material coupled to the coil. The magnetic bias field extends outward from the magnetic poles and can interact with unpaired electrons within the sample material to produce an electron resonance at a frequency, f_o. This frequency is related to the magnetic field by the relationship:

$$f_o = \frac{\gamma H_o}{2\pi}$$

where

γ = gyromagnetic ratio of electrons (17.61 x 10 for free electrons).

H_o = particular value of magnetic field intensity required for resonance (gauss).

For free electrons, the value of the frequency (f_o) is 2.8 x 10^6 H_o; and if the value of H_o is 100 gauss, the EMR resonant frequency is 280 MHz.

The field intensity, H, for a particular pole strength varies as the distance away from the plane of the poles. Thus for a specific pole strength, the electron magnetic resonance frequency for free electrons would vary as a function of locations within the material. Adjusting the pole strength will therefore allow forcing the electron magnetic frequency to any desired value, f_o, at any location within the sample. Treating the pole strength as a controlled variable as a function of time, the particular field intensity, H_o, required for electron resonance at frequency f_o can be made to sweep through the sample material. At any one time, the exact field intensity, H_o, occurs along a line of constant flux density.

Since the electron magnetic resonance energy absorption curve has a finite width, some response will be produced by electrons in material extending on each side of the exact H_o plot. The extent for a response equal to half of the center response is called a linewidth. The detection system model used for analysis makes use, therefore, of a bias magnet which may be varied in intensity to cause electron resonance for a particular operating frequency, f_o, to occur at any desired region within the material.

The RF coil and associated electronics detect the electron resonance response from the volume of material where the field intensity is within the electron resonance linewidth (about 5 to 8 gauss in coal) of the resonance intensity, H_o. Coal was found experimentally to produce a large response, while shale was found to produce only a small response. As the field is varied, and the resonance value, H_o, is swept over a coal/shale interface, there will be an abrupt change in the detected amplitude of the electron resonance response at the interface. Similarly, an abrupt change in amplitude is obtained by a sweep across the coal surface, which may be used to define the location of the coal surface. Knowing the location of these two points (i.e., the coal and interface surfaces), the thickness of the coal can be determined.

As the investigations proceeded, it was decided to develop a transient type of electron magnetic resonance system, since this approach appeared to offer promise of providing a higher useful sensitivity and a means of overcoming the instability and proximity problems characteristic of the balanced bridge type of steady state design. The basic problem of this approach lies in the fact that an RF pulse of only a few nanoseconds duration is required. In application, the sample is exposed to two short, closely spaced pulse bursts of radiofrequency energy at a frequency "corresponding" to the magnetic resonance of the electrons in the magnetic field. The response from the sample is a short burst of RF, which occurs at a time equal to the pulse spacing after the excitation. This response is at the resonant frequency of the electrons in the magnetic field and is typically very weak and spaced a few nanoseconds away from the second transmitter burst.

A block diagram of the basic transient EMR system is shown in Figure 3-41. Effort was also directed toward the design, assembly, and preliminary checkout of the pulse sequencer, the radiofrequency generator, and the receiver (radiofrequency amplifier and detector). In this system, the radiofrequency generator provides a pulsed output centered on a frequency of 400 MHz. The output format is in the form of a double-pulse sequence to provide a spin-echo mode of operation. The length of each pulse may be adjusted over the range of about 25 to 40 nanoseconds, and spacing between pulses may be adjusted over a similar range. It is expected that the repetition rate will be on the order of one megahertz or greater. The output power available from the RF generator (10 W peak) was believed to be sufficient for laboratory demonstration of the transient EMR concept using a coal sample in a simple coil, and was considered sufficient for at least a short range thickness gauge.

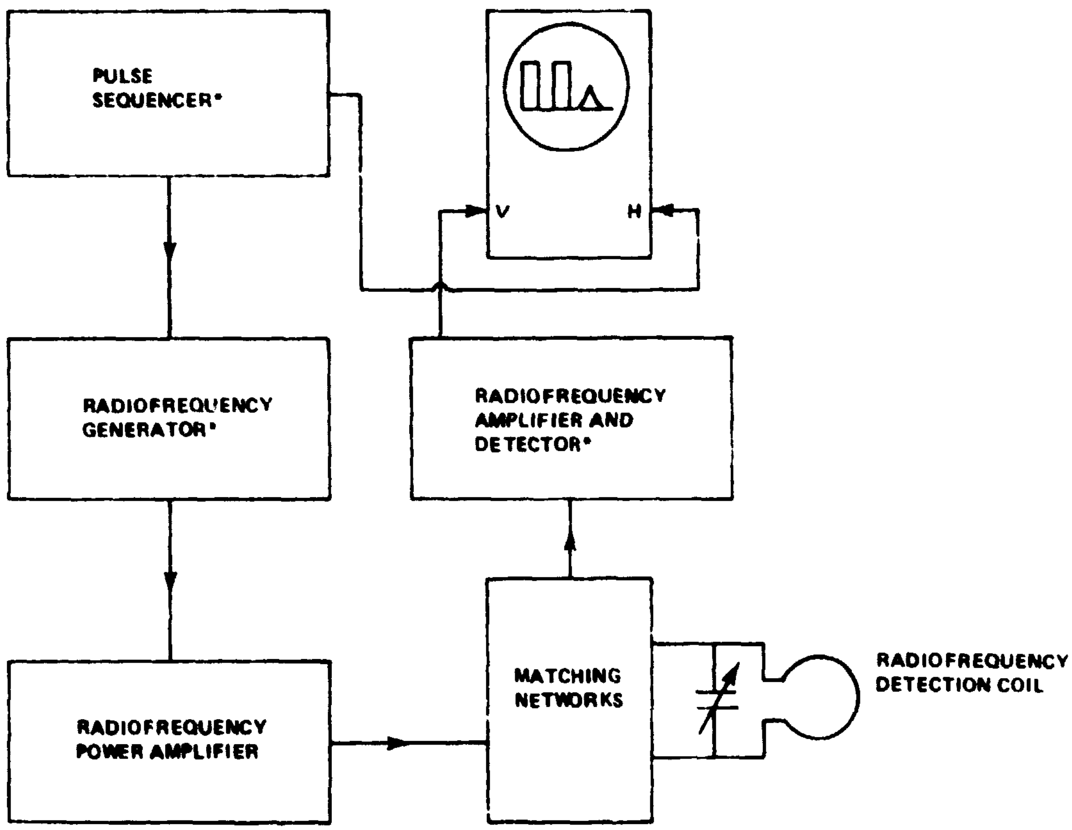


Figure 3-41. Block diagram (transient electron magnetic resonances detector).

The pulse sequencer, the radiofrequency generator, and the radiofrequency amplifier and detector were assembled in "breadboard" form during this period and tested. The results of these tests indicated that circuit modifications were required to reduce the recovery time following the transmitter burst and to reduce the leakage of the signal between the transmitter and the receiver.

The desired output from the radiofrequency generator part of the transient EMR system was a pulse of radiofrequency voltage at a nominal frequency of 400 MHz. The pulse width was 25 nanoseconds, and the rise and fall times on the order of 3 nanoseconds. It is further required that, during the time interval when the EMR signal is received (25 to 50 nanoseconds following the transmitter burst), the radio frequency voltage, other than the EMR signal, must be as near zero as possible.

The amplitude of any residual or spurious signal from the transmitter during this period must be small compared to the expected EMR signal level. This level is typically on the order of, or less than, one microvolt. The original design did not result in sufficient isolation, and steps were taken to improve the performance.

The radiofrequency generator was made up of the components as shown in Figure 3-42. The pulse of radio frequency begins as a MHz oscillator (tripled to 400 MHz). In the initial design, the 400 MHz output of the tripler was directly connected to the phase splitter. The two output phases, 0° and 90°, are both needed

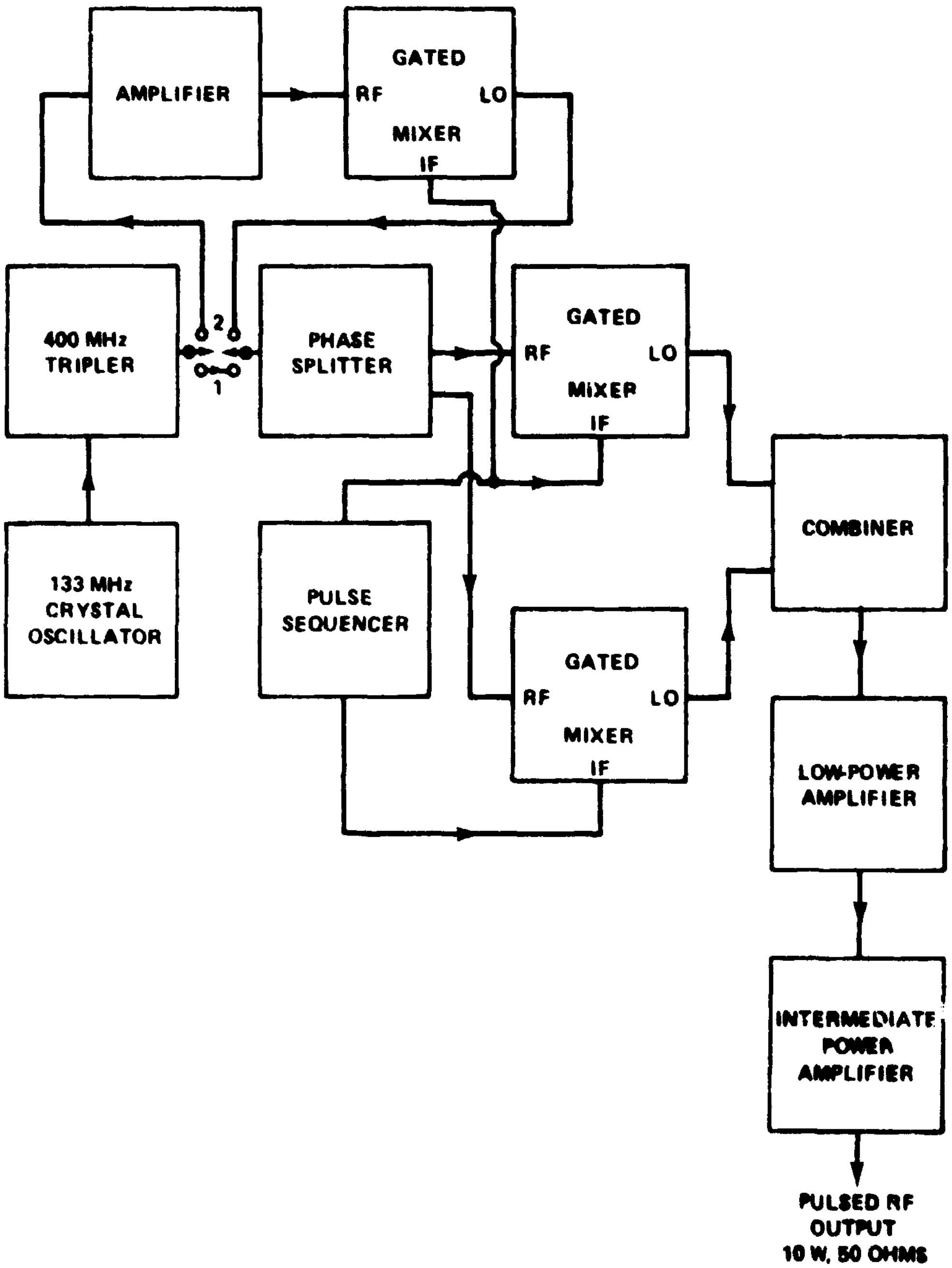


Figure 3-42. Radio frequency generator component of the transient EMR system.

for the EMR detection sequence; and each is fed to a double balanced mixer that acts as a gate which is actuated by pulses from the sequencer. The outputs of the two mixers are combined and amplified through a low-power amplifier and then through a power amplifier. An output of 10 W into 50 ohm load was obtained during each pulse.

To reduce the leakage between transmitter bursts, an amplifier and a second gated mixer were added between the tripler and the phase splitter. This change significantly increased the on/off ratio, but the need for still further isolation was apparent from test results. Alternate means of obtaining the improved results involved using gated oscillators (MECL-III NAND gates), but oscillation could not be obtained at a sufficiently high frequency to directly generate 400 MHz. However, by using delay lines for feedback, oscillation could be obtained at 280 MHz. The rise time for the output from these oscillators was found to be 3 nanoseconds, while the fall time was 5 nanoseconds. The spurious signals of significant amplitude following the pulses persisted for only 10 to 15 nanoseconds.

The revised EMR "breadboard" system used a homodyne receiver which offered a wide dynamic range and high sensitivity and was also tolerant of high levels of leakage signals at the detection frequency. These features reduced the requirement for complete elimination of leakage from the transmitter between pulse bursts.

A means of coupling the transmitter and the receiver to the sample coil using a wide bandwidth power divider was found to offer adequate efficiency and good isolation between the transmitter and receiver.

Laboratory tests were conducted using this modified transient EMR "breadboard" system on small samples of Diphenyl Picryl Hydrazyl (DPPH), a material rich in hydrogen ions in the sample coil. These tests were encouraging since it was the first time an EMR signal detection was observed at such low frequencies (400 MHz).

Also, an alternate method of EMR detection using a dual frequency technique (Fig. 3-43) to achieve stability was considered, since improvements made to the transient EMR system were not considered adequate for an accurate coal-depth measuring instrument. Limitations on further improvements were those of obtaining adequate separation of the transmitted signal from the desired EMR signal. This mixture of pulses results in the EMR signal being mixed with the residual transmitted signal and limits available sensitivity since small changes in the tuning of the sample coil and variations in the material in proximity to the sample coil, greatly affect the phase and amplitude of the residual signal.

Means for minimizing the above effect were investigated and incorporated in the model. Since further improvements were not readily forthcoming, an alternate transient approach using a self-detecting, pulsed oscillator was evaluated. This approach uses a single UHF field effect transistor (FET) and is, essentially, a separately quenched super-regenerative detector optimized for EMR applications. The pulse bursts generated by the oscillator have rise and fall times of approximately 5 nanoseconds with burst length adjusted to be on the order of 40 nanoseconds. A repetition rate of 1.0 MHz or higher was found to be necessary for optimum results. Operation detector was based on the effects of the transient (FID) EMR signal on the decay characteristics of the pulsed bursts of oscillation. The circuit of the detector is very simple compared to those previously used for transient EMR, and the results have been found by Southwest Research Institute to be superior in both inherent stability and usable sensitivity. EMR signal levels on the order of 50 millivolts were obtained directly from the oscillator-detector when a sample of DPPH was placed in the coil.

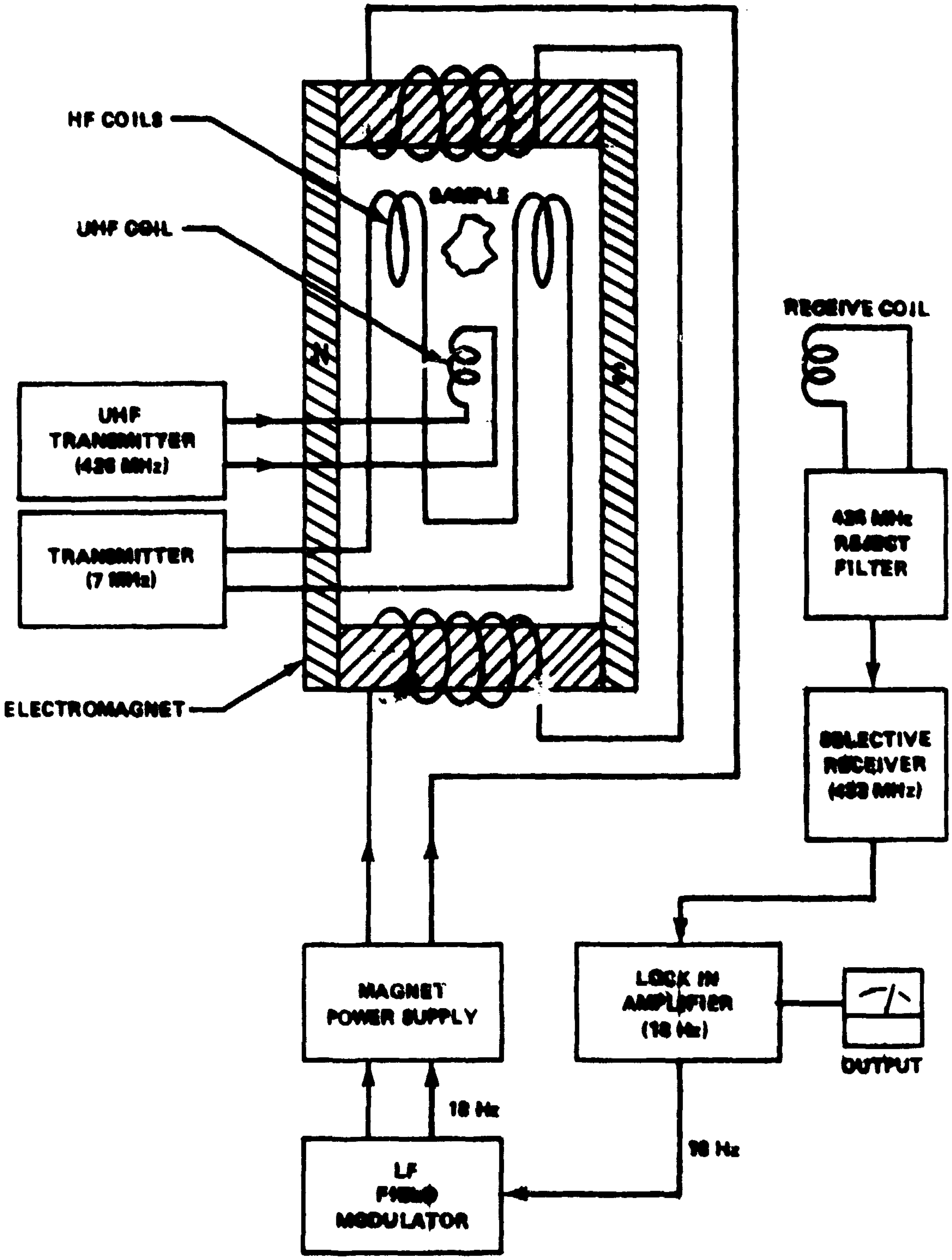


Figure 3-43. Block diagram of dual frequency EMR.

Further optimization and evaluation to determine the distance range over which a coal sample may be detected were also conducted.

Tests conducted using a relatively homogeneous magnetic field showed the capability of detecting blocks of coal at ranges up to 8 in. However, when a U-shaped magnet, as in a portable gauge, was used, the detection was limited to a range of approximately 2 in. In addition, the dynamic range of detection was less than 1/2 in.

The concept of good isolation and sensitivity of the dual frequency concept has been demonstrated. However, it appears that considerable effort would be required to develop a magnetic field that is homogeneous over a useful coal-depth range. Also, it is doubtful that such a field could be developed for a practical mine instrument within the time limits imposed by schedule constraints. This uncertainty, coupled with the emergence of more promising coal-thickness measurement systems, such as the natural background sensor, led to the discontinuance of the EMP effort at Southwest Research Institute.

3.1.6 Acoustic

The use of ultrasonics to measure coal depths was investigated under Contract NAS8-33093 with the Georgia Institute of Technology. These studies revealed that the attenuation of sound waves by coal (Fig. 3-44) was of sufficient magnitude to preclude its use as a practicable depth sensor. In view of these findings, others, such as coupling of the transducers to the coal surface, were not exhaustively investigated or modeled.

The investigations began at Georgia Tech by designing a digital sine wave generator for signal control and the use of matched transducers (which were based on the echo cancellation concept). This experimental equipment eliminated the disadvantages of using the pulse as a test signal. Those disadvantages were identified as follows: the ill-defined frequency spectrum, lack of an exact phase control of the transmitted and received signals, lack of identification of the beginning and end of the pulse, and lack of adjustment capability of the pulse duration.

The sine wave generator is a unique device allowing control of the frequency, cycles, amplitude, and phase of a signal. It produces two sinusoidal bursts of substantially identical waveforms, but with an adjustable delay between their starting times.

The bursts are derived digitally from an external frequency standard (crystal clock), with a frequency of 5 MHz; the master frequency for sine wave synthesis can be any integer fraction of this clock frequency. The period of each cycle is ten times the reciprocal of that integer fraction of the master frequency. The duration of each burst can be adjusted, from one to nine periods of the waveform, in steps of one period. A delay counter is started coincident with the sinusoidal waveform generator. Upon completion of this pre-set delay interval, a second sine wave generator is started, which then generates the same number of cycles as there were in the first burst. The delay interval can be adjusted to any integer number of master clock cycles. Thus, the two sine wave bursts can be delayed by an integer multiple of 1/10 of a period of one sinusoid. The three-decade delay counters allow the total delay between the two bursts to be as much as 99.9 cycles. Sinusoidal output frequency, the number of cycles in a burst, and the delay between two successive bursts are all adjustable during the course of the experiment.

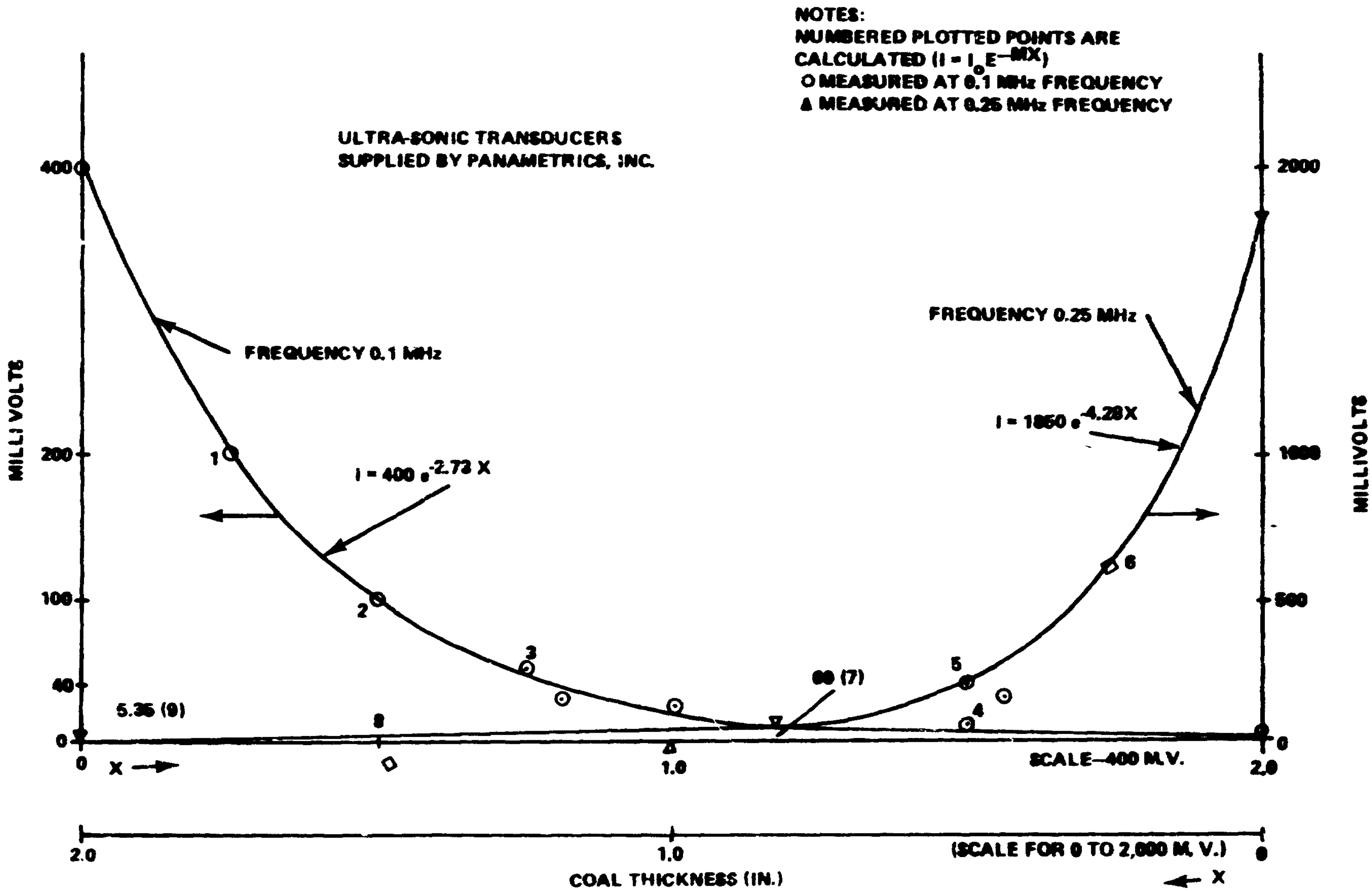


Figure 3-44. Calculated curves fitted to measured acoustic data.

The experiment was performed using a tank of water made of plexiglas and fitted with aluminum cylinders for housing the transducers and an aluminum plate for holding the suspended coal sample. The aluminum plate extended across the width of the tank to prevent spurious diffraction effects in the received signals.

The results of the experiments in which the attenuation coefficient was measured are shown in Table 3-7. These values, with the exception of that measurement for the 1.96-cm slab (believed to be spurious), are in good agreement with previously published values, as well as results obtained by MSFC laboratories (Fig. 3-44).

TABLE 3-7. PHASE VELOCITY AND ATTENUATION CONSTANT FOR COAL MEASURED BY SUBSTITUTION METHOD

Sample Thickness (cm)	Speed of Sound (m/sec)	Peak to Peak Voltage Without Sample (mV)	Peak to Peak Voltage with Sample (mV)	Voltage Ratio	Total Time Immersed in Water (min)	Nepers/cm	Nepers
1.38	2510	952	219	4.35	20	0.97	2.44
1.51	2490	928	149	6.24	20	1.13	2.8
1.63	2440	920	106	8.65	20	1.24	3.04
1.96	2550	968	227.2	4.26	20	0.662	1.69
2.52	2420	960	72.8	12.19	20	0.97	2.44

The experiments performed by Georgia Tech confirmed the high attenuation of coal for ultrasonic waves which made their use as a coal thickness measuring instrument impracticable. The work was concluded in favor of the more reliable and more feasible natural background sensor as a coal-thickness measuring instrument for the vertical control application.

3.1.7 Hydraulic Drill

Application of hydraulic drilling to coal interface detection was investigated by Dr. David Summers, Director, Rock Mechanics and Explosives Research Center, University of Missouri at Rolla, Missouri, under the terms of grant NSG-8055 from Marshall Space Flight Center.

The configuration selected for the hydraulic drill consists of a 1/4-in. diameter pipe, whose length has been offset in such a way that, when rotated, the offset portion of the pipe transcribes a circle of approximately 1-1/2 in. diameter. Ejection of water at 9,000 psi impinging upon a target of coal for 2 sec cuts a cylindrical hole through it, to depths of about 8 in. It was also found that, with targets of shale, sandstone, and limestone, the jet will also penetrate 8 in., removing an annular volume of material, but leaving the central core.

A laboratory version of the device was tested, during which the cutting characteristics mentioned above were demonstrated on sample materials.

The sensing device considered for this application is the optical range finder used on the Koncia camera, developed by Minneapolis-Honeywell. The range finder uses two mirrors for focusing and an integrated circuit for image comparison, imposed upon two sensor arrays. It produces an output voltage that is maximum when the two images impinging on the detector are most alike. At that point, the integrated circuit also produces a step function voltage change that, by means of external control circuitry, automatically positions the camera lens. It was proposed by Dr. Summers that the same signal be used as a command signal. The range finder senses an 8-in. depth or the zero depth of a cored hole, thus effectively discriminating coal or non-coal

A more sophisticated unit for testing coal and shale samples was fabricated. High-pressure water, mixed with a small amount of soluble oil, was provided by a triplex pump. The assembly was tested in the Jet Cutting Facility of the Rock Mechanics and Explosives Research Center. The working fluid was transmitted through a 0.5-in. internal diameter high-pressure hose to a manifold. This manifold (1.6-gal capacity), designed to remove the pulsations from the fluid flow, also served as a point where the pressure could be monitored using a conventional bourdon tube pressure gauge. A high-pressure (30,000 psi burst) hose was then used to conduct the fluid to the test stand.

The test stand consisted of a table upon which samples could be placed above a rotary drilling system. The table was constructed with a shutter mechanism mounted under a central orifice on the support platform. The shutter, operated manually, was used to control the duration of the jet action on the target sample.

The rotary drilling system consisted of a Harwood swivel coupling supplied with fluid by the flexible hose, to which a vertical length of high-pressure tubing was coupled to the cutting nozzle. The tubing (1/4-in. I.D., 9/16-in. O.D.) was offset along its longitudinal axis so that, as it rotated, the ensuing jet would inscribe an annulus. Three separate tubing sections were prepared so that the degree of eccentricity could be changed from 1/2 in. to 3/4 in. to 1 in. Rotation of the pipe was achieved through a sprocket and chain driven by a hydraulic motor.

The flow of oil to the hydraulic motor was variable within a fixed range so that the speed of rotation could be adjusted up to 1,000 rpm. Four nozzles were used in the test program having diameters of 0.02, 0.03, 0.04, and 0.064 in. The nozzles, attached to the end of the tubing using pins to ensure exact location for contour matching. were held in place by a retaining head.

Bituminous coal samples were obtained from a strip mine in the Bevier seam in northwest Missouri. The samples were interlaced with lenses of pyrite. Samples of sandstone and shale from the overlay were also collected.

The samples were cleaned to remove loose material and made into specimen blocks 28-in. by approximately 4-in. thick. The targets were prepared by placing sandstone or shale in the bottom of a pre-formed wooden box upon which a block of coal was placed. To protect the coal samples from further weathering, a concrete hydrite mixture was then poured into the box in quantities sufficient to cover the upper coal surface. The samples were cured for 3 days, after which the wooden frame (box) was removed and targets allowed to age for 2 weeks. The protective concrete cover was removed from the coal surface before testing.

In addition to the targets prepared from samples collected from the Bevier seam, twelve targets were prepared using Berea sandstone, the underlying rock material.

Proof of the technique depended upon demonstrating that a water jet would cut out a cylindrical slug through the coal, but would not penetrate the overlying sandstone or shale. Therefore, initial verification tests were performed.

In previous tests using Berea sandstone, it was found that the jet will cut this material more readily than other rocks. It was therefore decided to use this material to parameterize the jet characteristics required to cut a slot rather than a hole.

In the first series of tests, three offset radii and four nozzle diameters were tested. Results are shown in Table 3-8. The tests were performed over a 5-sec period in order to give the maximum time for damage to the rock, and were performed, with the exception of the tests with 0.064-in. diameter nozzle, at a jet pressure of 10,000 psi. Because of the large nozzle diameter and the limitations of the pump, the tests using the 0.064-in. nozzle were carried out at 8,800 psi.

The results of the tests revealed that the largest nozzle radius would consistently cut an annulus in the rock rather than removing some of the central core, although the smaller diameter jets cut an annulus even at the smallest offset radii of the cutting arm. The first phase of the program could therefore be described as successful insofar as demonstrating that the water jets would cut a circle in the rock while leaving the central core intact.

Additional tests were conducted using a standoff distance of 2.25 in. with 5-sec exposure times to determine what conditions were necessary for the water jet to adequately penetrate the coal to the overlay material and "slot" it while removing all of the coal.

TABLE 3-8. INFLUENCE OF JET PARAMETERS ON CAVITY CONFIGURATION

Nozzle Diameter (in.)	Pressure (psi)	Rotational Speed (rpm)	Offset Radius (in.)	Time (sec)	Diameter of Hole Cut/Annulus (in.)	Depth of Cavity/Annulus (in.)
0.02	10,000	750	0.5	5	0.56	2.5
0.02	10,000	750	0.75	5	1.13	2.5
0.02	10,000	750	1.00	5	1.38	1.75
0.03	10,000	750	0.5	5	0.69[a]	3.31
0.03	10,000	750	0.75	5	0.88	3.38
0.03	10,000	750	1.00	5	1.63	2.00
0.04	10,000	750	0.5	5	0.50	3.13
0.04	10,000	750	0.75	5	1.38[a]	4.00
0.04	10,000	750	1.00	5	1.50	2.63
0.064	8,800	750	0.5	5	1.00[a]	7.50
0.064	8,800	750	0.75	5	1.00	5.81
0.064	8,800	750	1.00	5	1.25	5.63

a. No central core remained.

The results of these tests (Table 3-9) showed that the smaller nozzles were not adequate to the task required. Although the 0.04-in. nozzle, for example, was capable of penetrating up to 6-1/2 in. into the coal within the 5-sec period of the test, the requirements specified that the system be able to discriminate (penetrate) up to 8 in. of coal. It was therefore concluded from these tests that it would be necessary to use the 0.064-in. nozzle in order to cut through the required thickness of coal within the time frame required. It was also noticed that, in those tests using the smaller nozzle diameters, the jet would not cut a straight-walled cylinder through the coal, but rather the hole would "cone" toward the rear so that the 1-5/8-in. diameter hole at the surface was reduced to 1 in. at the bottom, producing an insufficient area at the interface to permit slotting of the shale surface.

TABLE 3-9. JET PENETRATION THROUGH COAL

Test Number	Nozzle Diameter (in.)[a]	Hole in Coal	Hole in Rock
17	0.02	3 in. deep - did not remove all the core	did not reach the rock
18		3.25 in. deep - removed all core	did not reach the rock
25		5.0 in. deep	did not reach the rock
16	0.03	4 in. deep - tapered from 1.5 in. to 1 in.	no significant damage
19		2.25 in. deep - tapered from 1.63 in. to 1 in.	did not reach the rock
24		4.75 in. deep	did not reach the rock
15	0.04	4 in. deep - removed all coal	no significant damage
20		6.5 in. deep - tapered from 1.5 in. to 1 in.	no significant damage
23		2.38 in. deep	did not reach the rock
14	0.064	4 in. deep - removed all coal	cored from 1.87 in. to 0.5 in.
22		6.5 in. deep - removed all coal	2.75 in. deep slot

The tests were carried out with a nominal 2.25-in. standoff and at approximately 750 rpm jet rotation speed on a nominal 1-in. eccentric radius with a 5-sec jet exposure time.

a. Tests at 10,000 psi, apart from the 0.064-in. diameter nozzle where the pressure was 8,800 psi.

A test was performed with the largest of the nozzles capable of operating at 10,000 psi (0.04-in. nozzle) to determine the effects of varying revolutions on cutting depth and to determine if the jet could cut completely through the coal within an adequate time. These three tests described (Table 3-10) indicated that, while the jet was capable of cutting through a 6-in. sample of coal within 5 sec, the revolutions were not a factor in the achieving penetration, and that the jet was not capable of cutting to the necessary depth of coal when the exposure time was reduced to 3 sec. This confirmed the conclusion that the largest nozzle diameter would be required for the test equipment, particularly since it was noted that in all four of the tests the hole diameter was reduced considerably with depth into the hole.

TABLE 3-10. EFFECT OF TIME AND ROTATION SPEED ON PENETRATION OF COAL

Run	Time (sec)	Rotational (rpm)	Speed Depth (in.)	Comments
26	5	835	6.25	hole tapered
27	5	200	6.50	hole tapered
28	3	835	5.13	hole tapered

The tests were carried out with a 0.04-in. diameter nozzle, at a nominal rotational eccentricity of 1 in., 2.25 in. standoff, at 10,000 psi jet pressure.

As a result of these tests, it was decided to conduct further tests examining the potential benefits to be achieved by increasing the pressure of the 0.04-in. diameter jet to determine whether, in fact, the jet could be made to cut through the 8-in. of coal in 3 sec at an increased pressure. As a result, three tests were carried out successively at 8,000, 10,000, and 12,000 psi (Table 3-11). It was determined from these tests that the jets were still incapable of cutting a depth of greater than 5-3/4 in. even at 12,000 psi. It was therefore concluded that the only alternative was to use the 0.064-in. nozzle diameter.

An additional series of tests was carried out at 4,000, 6,000, and 8,000 psi using the 0.064-in. nozzle. It was found that, for the 3-sec exposure at 4,000 psi (Table 3-11), the sample was not completely penetrated; however, at 6,000 and 8,000 psi, the jet cut completely through the coal and into the sandstone in 3 sec. With a pressure of 8,000 psi, the jet not only went through the coal, but also completely through the sandstone. In consequence, it was determined to carry out further tests reducing the exposure time to 2 sec. This was the shortest practical duration of the tests that could be performed with the system as constructed. Six tests then were carried out at a 2-sec exposure time with a 0.064-in. nozzle diameter and at various jet pressures.

At 4,000 psi, the jet cut only 4-1/2 in. into the coal; but in the first test at 6,000 psi, the cut went completely through the coal to the underlying sandstone, a distance of some 6 in. Similarly, where the tests were carried out with coal backing on shale, within the 2-sec time and 8,000 psi, the water jet cut completely through the coal and into the shale. In further experimentation, it was found that, with 6,000 and 8,000 psi pressure, the water jet would completely penetrate through the

TABLE 3-11. EFFECT OF JET PRESSURE AND EXPOSURE TIME ON COAL PENETRATION

Run Number	Nozzle Diameter (in.)	Jet Pressure (psi)	Time (sec)	Cut in Coal	Cut in Rock
31	0.04	8	3	5.06 in. deep hole	did not reach rock
29	0.04	10	3	5 in. deep hole	did not reach rock
30	0.04	12	3	5-3/4 in. deep hole	no significant change
34	0.064	4	3	4.75 in. deep hole	did not reach rock
33	0.064	6	3	6 in. deep hole	marked rock
32	0.064	8	3	6 in. deep hole	3 in. deep cylinder left (to back of block)
38	0.064	4	2	4.5 in. deep hole	did not reach rock
35	0.064	6	2	6 in. deep hole	slotted rock
39	0.064	6	2	8.38 in. deep hole	slotted rock
36	0.064	8	2	6.75 in. deep hole	shale backing disintegrated
37	0.064	8	2	6.75 in. deep hole	shale backing disintegrated
40	0.064	8	2	8.5 in. deep hole	slotted sandstone

coal into the sandstone within a 2-sec time exposure. In both cases, the water jets completely removed all the coal, but left the sandstone in a slotted condition. This result, it is felt, was consistent enough to verify the concept originally proposed, which was to use a water jet to discriminate between coal and shale and also to demonstrate that this could be done within a time short enough for the operation to be carried out on a longwall face.

It has been demonstrated that it is possible to penetrate through more than 8 in. of coal in less than 2 sec, removing all the coal from the cylinder drilled out, but leaving the central core present where the jet penetrates into sandstone. It can therefore be concluded that high pressure water jets can be used as a discriminating system between coal and the overlying roof rock in the manner proposed. Insofar as the pump at 8,800 psi put out 10 gal/min and at 8,000 and 6,000 put out correspondingly less fluid and the holes were drilled in less than 2 sec, the amount of water that would be required to drill each hole would be on the order of 1.3 quarts.

The hydraulic drill investigations were terminated because no satisfactory technique for measuring the depth of the hole, that is, the thickness of the coal, could be found. Also the water and its pressurization system was considered too complex for use as a coal-depth sensor for the vertical control system.

3.1.8 Surface Recognition Sensor

The surface recognition coal interface detector incorporated two sensing devices, a penetrometer and two reflectometers, to identify surfaces. The penetrometer used the hardness of the test surface as a means of detection, and the reflectometer used surface reflectance as a means of detection. Both devices were incorporated into a single instrument designed and fabricated by MSFC (Fig. 3-45).

For the penetrometer test, a shale sample was placed over one reflectometer, and non-coal was indicated. When it was removed, coal was indicated. The shale was moved about over the device continually during the portion of this test that the shale was over the device. This test was repeated 20 times with 100 percent correct indication (Table 3-12).

The coal sample was placed over the reflectometer, and coal was indicated. The coal sample was moved about over the face of the device. When the coal was removed, coal was still indicated. This test was repeated 20 times, with coal indicated at all times. After these tests, shale was again placed over the device; and non-coal was indicated, verifying that the device was still working.

The Integrated Tests (Using the Voting Circuit): Each system, impact penetrometer, reflectometer No. 1 and No. 2, was tested individually to assure proper operation. Then the conditions shown in Table 3-13 were imposed upon the surface recognition device, and the output recorded. Following these tests, each system was again tested separately.

The instrument was not tested in situ; and, in view of the evolving ground rules for the longwall guidance and control system, especially the roof non-contacting decision and the role of the sensitized pick in the control logic, this sensor was shelved. However, it does successfully function in the surface recognition role and can be used for that purpose.

3.1.9 The Vibration Sensor

The vibration sensor was developed by the General Electric Company of Schenectady, New York, for the Bureau of Mines. It was designed to measure vibrations transmitted from the cutting drums with coal/shale detection based on the higher vibration levels expected from cutting shale.

Additional test data was required by the Bureau (later the Department of Energy) to more fully evaluate its operability. MSFC was requested to incorporate an in-mine test into the underground testing program to be performed on the sensitized pick by the General Electric Company.

The instrument was added to the test configuration scheduled for Kaiser's mine in Raton, New Mexico, during late summer of 1980. The presence of a "middleman" (a stratum of rock within the coal) created a condition that interfered with the proper

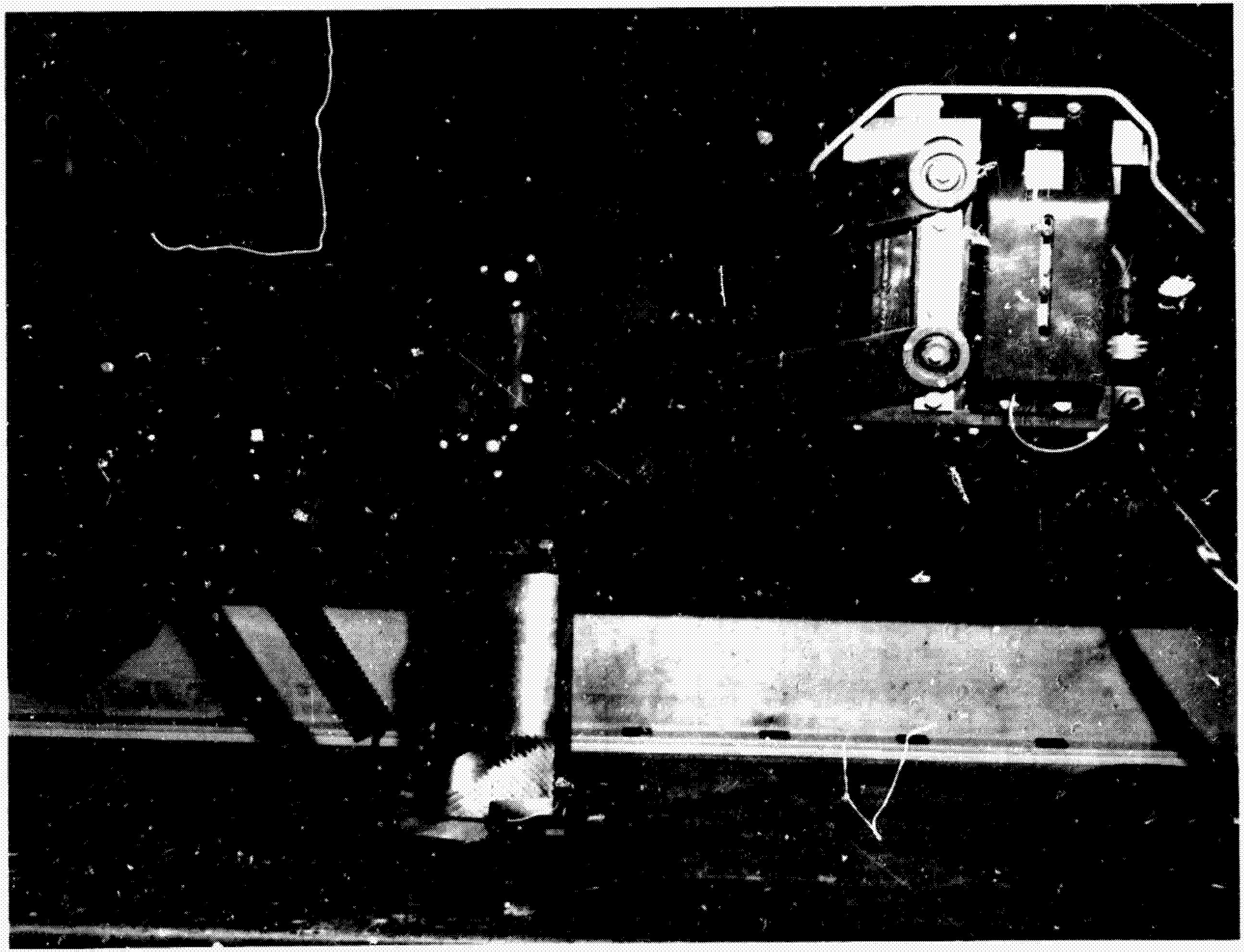


Figure 3-45. The surface recognition sensor.

TABLE 3-12. RESULTS OF PENETROMETER TESTS

Test Samples	Number of Cycles	Results (Indication on Readout)
Fire Brick	1,000 (continuous)	Non-coal
Fire Brick	2,000 (on-off)	Non-coal
No Target (Nothing)	1,000 (continuous)	Non-coal
Coal	1,000 (continuous)	Coal
Coal	2,000 (on-off)	Coal
No Target (Nothing)	1,000 (continuous)	Non-coal

TABLE 3-13. RESULTS OF SURFACE RECOGNITION TESTS

Reflectometer R_1	Reflectometer R_2	Impact Penetrometer (I.P.)	Result
Coal	Coal	Coal	Coal
Coal	Coal	Fire Brick	Coal
Coal	Shale	Coal	Coal
Shale	Coal	Coal	Coal
Shale	Coal	Fire Brick	Non-coal
Coal	Shale	Fire Brick	Non-coal
Shale	Shale	Coal	Non-coal

operation of the instrument. Meaningful data could not be collected and the test was judged inconclusive. No further tests were performed using this instrument.

3.1.10 Other Sensing Concepts

Since the initial problem posed by the Bureau of Mines (Department of Energy) was to identify a means or technique of locating the coal/shale interface, a number of techniques taking advantage of coal/shale's physical and electrical properties were investigated. These either failed to satisfy known operational requirements imposed by the mining machine or the characteristics of the shale and/or coal were not compatible with the measuring technique.

These techniques included mechanical drills and saws, electrical resistance and capacitance, and infrared. These were subjected to laboratory testing and later discounted as practicable sensing devices.

The mechanical saws and drills physically cut through the coal into the shale bed. Upon encountering shale, the resistance to the cutting action increased, causing an increased current to be required by the motor to maintain a given rate of rotation. At the point of increased current demand, the shale boundary existed; and the measurement of coal thickness read off a vernier. While the technique was suitable for stationary measurements, its use under dynamic conditions required a more complicated mounting frame to compensate for the shearer's movement, an arrangement which is not compatible with the design of the control system.

Electrical resistance- and capacitance-measuring instruments required coupling into the roof. In the case of electrical resistance, no discriminator could be identified. In the case of capacitance measurements, the complexity of coupling into the roof and the practical problems of mounting and interfacing with the shearer were impracticable. Because safer, more reliable techniques of coal depth measuring were available, this method was discounted.

Infrared was investigated, and no discrimination between wet coal and wet shale was found.

A variation of the sensitized pick, in which a thermistor was mounted in the cutting bit, was investigated. It was theorized that this arrangement could possibly detect the variations in rock- and coal-cutting from thermal gradients caused by resistance of rock to the cutting action. Preliminary laboratory experiments indicated that the operating principle was not feasible, in view of the cutting environment of the shearer.

3.2 Cut-Followers

A key element of the vertical control system is the measurement of the distance from the hub of the rear and forward drums to the roof formed by the last and present cut, respectively.

Four instruments were designed and evaluated to make the measurement: mechanical arm, radar, acoustic device, and an optical measuring device.

The mechanical arm was not adopted to the experimental mine configuration since it was considered vulnerable to damage from coal mining operations, and since it had to be in physical contact with roof, thus interferring with mining operations. In view of these considerations, it was decided that a non-roof-contacting measuring instrument would be more desirable.

3.2.1 Radar

The frequency modulated continuous wave (FM/CW) radar technique for distance measuring was pursued as an in-house development at MSFC. The choice of this measuring system was made primarily because of the success of this technique in

aircraft radar, experience gained by MSFC personnel in the CID (FM/CW) radars, and the immediate availability of components and instrumentation for design, fabrication, and test of the radar. During the period of development, two models, based on operating frequencies, were fabricated and tested. They were the 12 to 18 Giga Hertz (GHz) model and the 35 GHz model. The higher frequency range model was adopted in order to achieve a narrow beam width to fit into the exposed roof between the front edge of the chock canopies and the coal seam.

The 12 to 18 GHz radar contained a YIG oscillator as a signal source. This oscillator frequency is modulated to 12 to 18 GHz by a 100 Hz triangular wave form. Figure 3-46 is a block diagram of the radar as originally designed and fabricated. It consists of two separate parts. The part shown at the top of Figure 3-45 is the transmitter/receiver section. A portion of the YIG oscillator signal is coupled to a mixer by a 10 dB directional coupler. The remainder of the signal is transmitted by the horn antenna. The return signal that is reflected by the coal surface is received by the horn antenna and input to the mixer by a 3 dB directional coupler. The resultant signal from the mixer has a frequency component that is directly proportional to the two-way air distance between the radar and the coal surface. The calibration constant of the radar is 80 Hz per centimeter of range. This is determined by the FM/CW radar equation:

$$\frac{f}{r} = \frac{4 \Delta rf \ \varepsilon \ f_m}{c} \quad ,$$

where

f = frequency

r = range in cm

Δrf · 6 GHz

f_m = 100 Hz

ε = 1 (air)

$c = 3 \times 10^{10}$ cm/sec.

The different frequency from the mixer is not zero for zero target range, because the electrical length from the 10 dB coupler to the mixer is not equal to the electrical coupler. In addition to the different frequency due to the range, other frequencies are present. The frequencies are due primarily to reflective form of the component mistakes and to false targets. The second part of the radar (lower portion of Fig. 3-46) contains a bandpass filter to select the desired frequency spectrum and a pulse-counting type of frequency detector that generates a voltage that is proportional to range.

Initial tests of the radar were very successful. The range error was less than 2 percent over a dynamic range of 140 cm. The target used was a smooth surface concrete block. Temperature tests were conducted on the various portions of the radar to determine error sources. One of the major error sources was the frequency

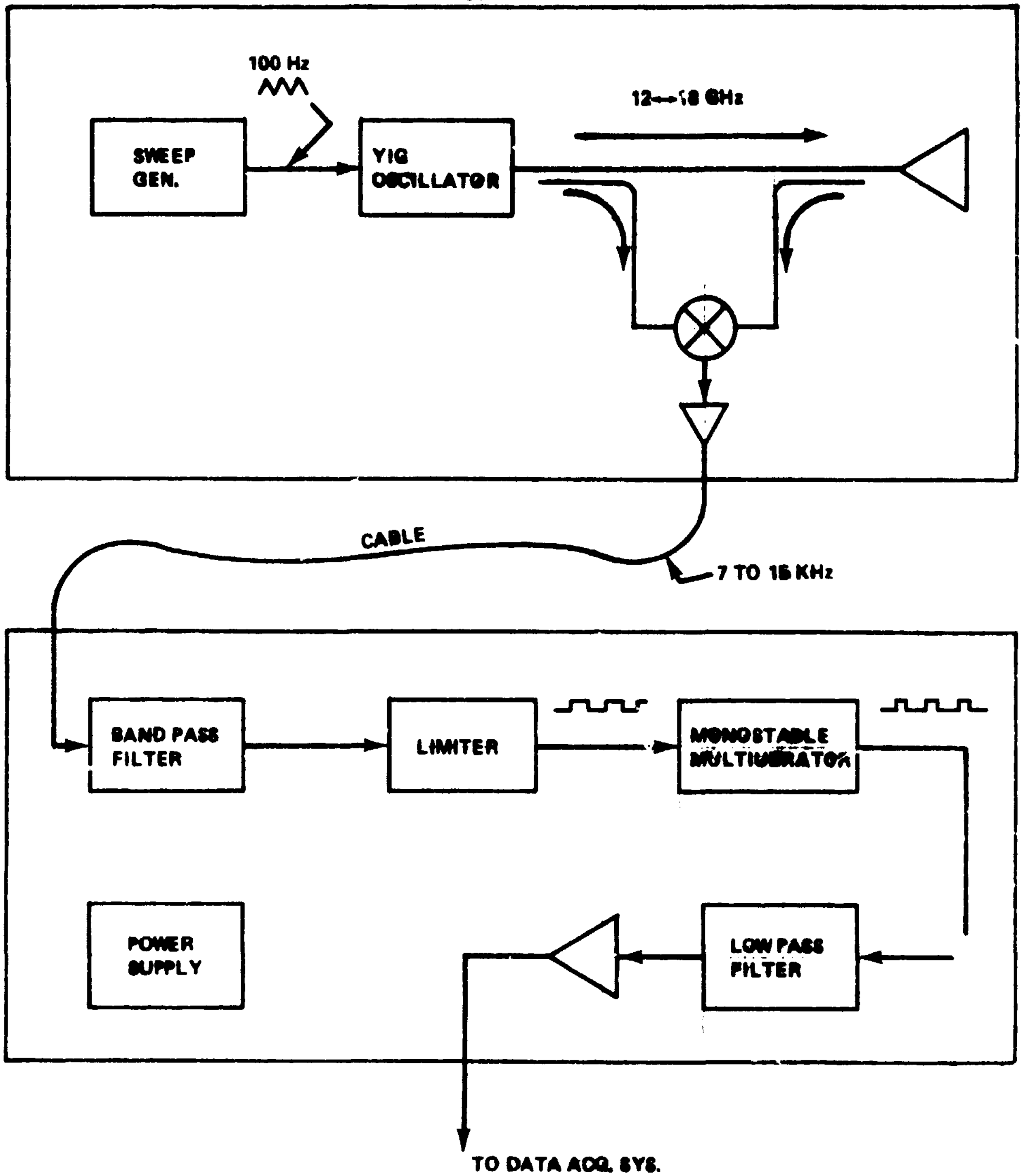


Figure 3-46. Schematic, last cut follower radar.

of the 100 Hz triangular wave generator. Initially, this generator used an operational amplifier in an integration configuration where external resistors and capacitors set the operating frequency. This generator was replaced with a digital sweep generator consisting of an up/down counter and a 12-bit D/A converter. The frequency reference is a 1-MHz crystal oscillator. This change resulted in a sweep generator with excellent linearity and frequency stability.

The radar was tested above ground on the Joy Longwall shearer at the Bruceton facility with results shown in **Figure 3-47**. This data was recorded while the machine trammed along the face. As can be seen, the recording appears quite noisy with some signal dropout. Upon close observation of the machine while it was moving under the ledge, it is estimated that the LCF was moving vertically 1/2 to 1 in. peak-to-peak because of the machine's motion. In addition, the surface roughness of the roof varied 1/2 to 1-1/2 in. Considering the above, it is not unreasonable to expect the unsmoothed radar data to appear noisy. It is therefore judged that signal variations of those in Figure 3-46 of approximately 2 in. or less could be considered real, and those measurements greater than 2 in. considered signal dropouts.

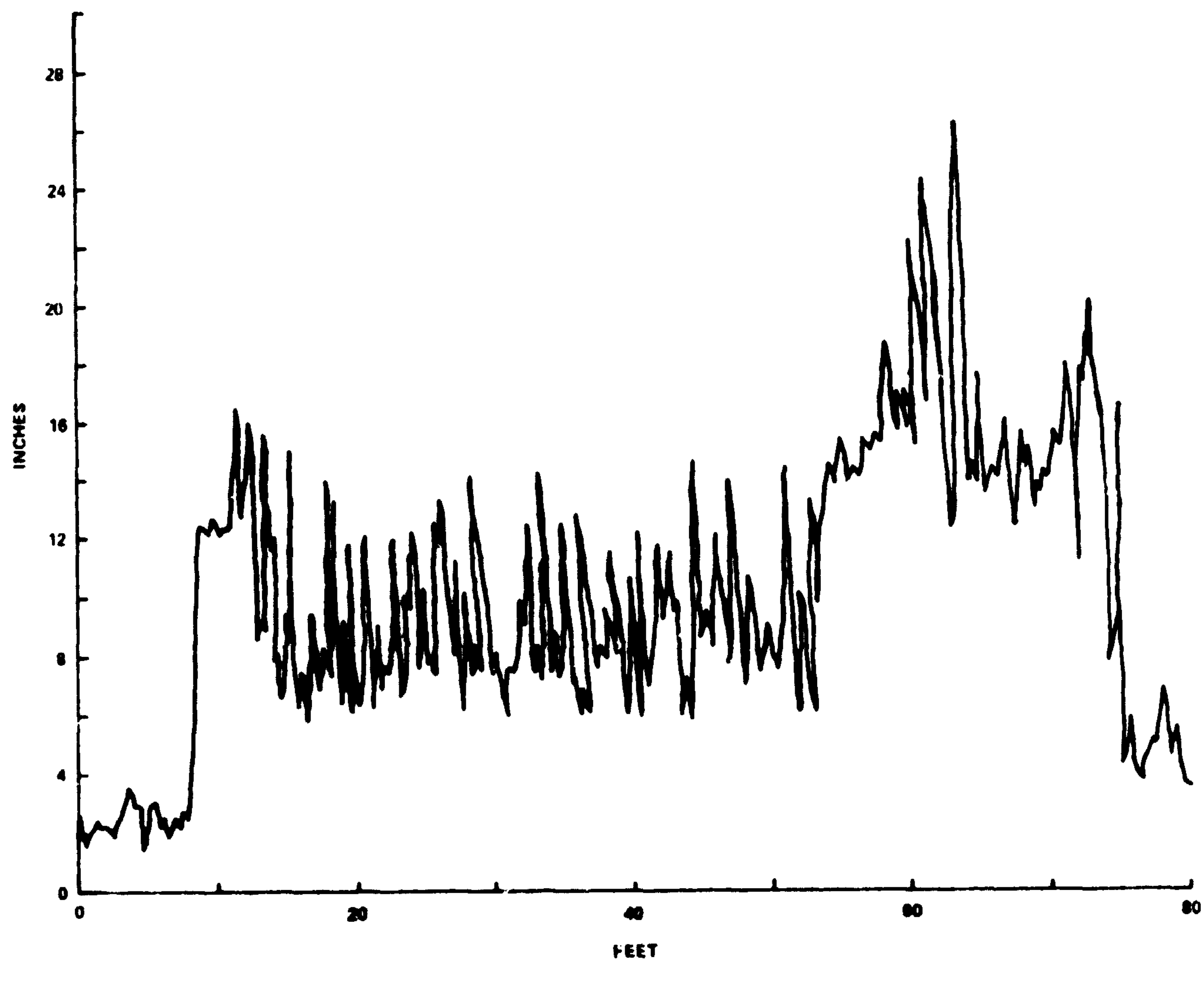


Figure 3-47. Bruceton test results last cut follower radar.

The data used to plot Figure 3-48 was obtained from data recorded by the HP9825 system controller. During these tests, the HP9825 sampled the radar signal once per second and stored the information digitally on magnetic tape. During the initial testing, the detection electronics provided no smoothing or filtering of the output data. In order to simulate smoothing, the data stored on the magnetic tape was weighted to simulate 4-, 5-, 6-, and 20-sec smoothing. Figure 3-48 is a plot of the smoothed data. Each plot was intentionally offset vertically to allow easy comparison. It was judged that a 4-sec smoothing would be sufficient to provide an average measurement and avoid signal time delays that would significantly reduce the effectiveness of the control system. Figure 3-49 is the results of a test with and without 4-sec smoothing. The step in the roof at approximately 60 ft into the run was actually measured to be about 7 in., which compares favorably with the radar's output.

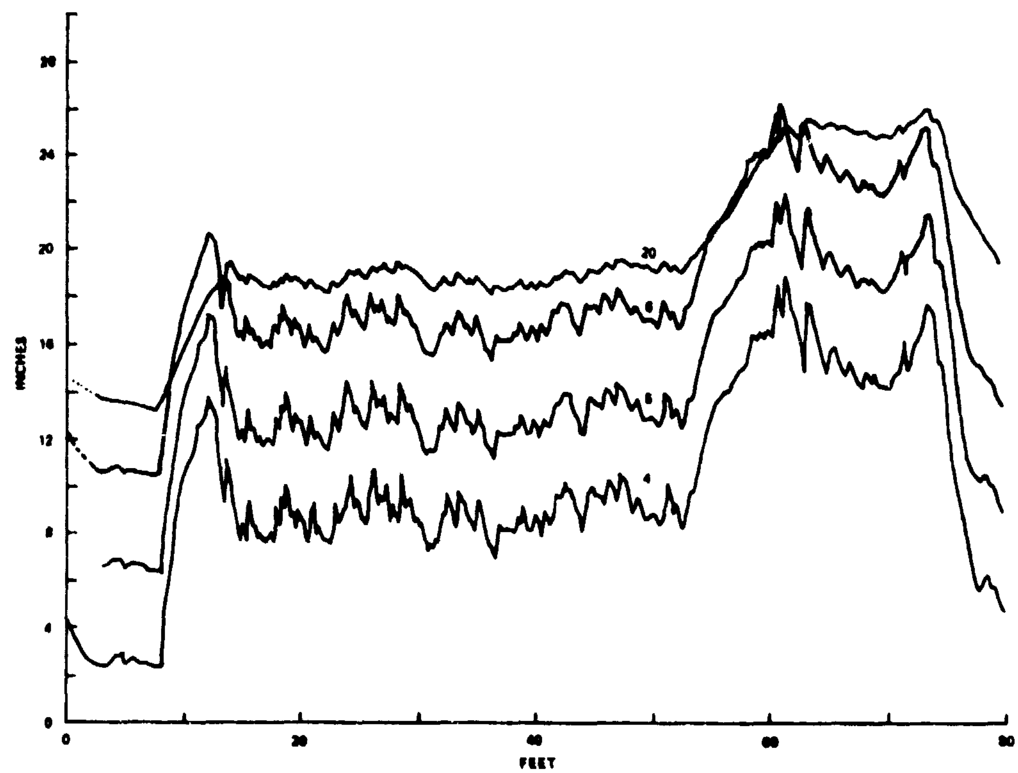


Figure 3-48. Radar cut follower Bruceton test results.

After the initial testing, it was decided to modify the LCF to provide signal smoothing. In order to implement a simple change in the field, a 4 sec RC filter was added to the signal detection electronics. Figure 3-50 is a plot of the LCF output during a test. Notice that the apparent jitter or noise is greatly reduced from that of Figure 3-47. The roof had been cut between the two tests, accounting for the different roof profiles.

Smoothing or low pass filtering of the radar output is considered a reasonable way to provide a measurement of the average roof surface. Subsequent versions of the radar included data smoothing. The problem of signal dropout was more complex and required moderate modification of the detection electronics. The principal causes

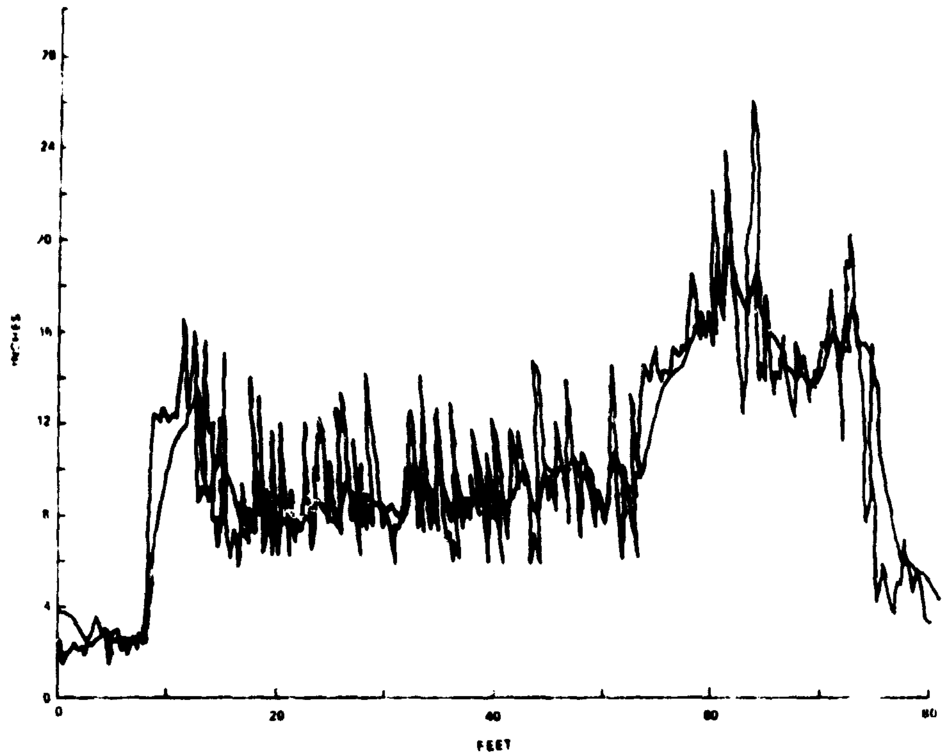


Figure 3-49. Radar data test No. 1 Bruceton test.

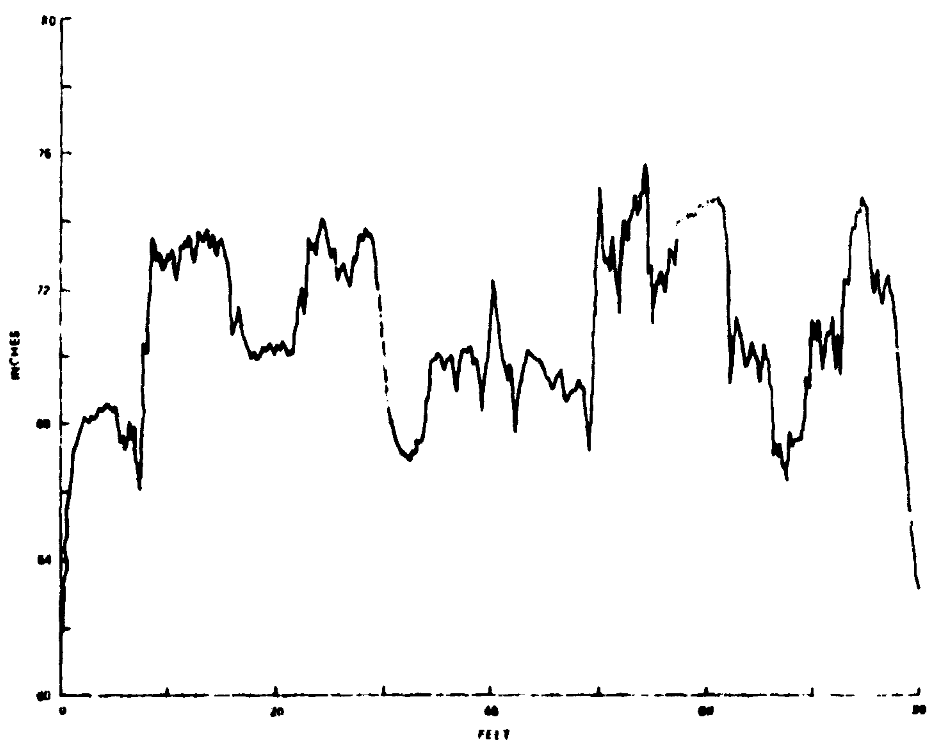


Figure 3-50. Radar data test No. 23 Bruceton VCS Test.

of signal dropout were identified as the lack of signal return from the roof surface and the multiple returns from the roof surface. Lack of signal return is caused by the angle of incidence of the radar beam to the roof surface deviating from normal and by the roof surface roughness causing a non-specular return.

The frequency-to-voltage converter of the radar was redesigned to essentially eliminate or significantly reduce errors due to signal dropout and multiple returns. Presently, the frequency-to-voltage converter is a pulse-counting type followed by a 4-sec time constant RC filter. The effect of zero-crossing errors is greatly reduced by the filter. The accuracy of the radar, however, is directly proportional to the zero-crossing error rate. It is intended to include a signal amplitude detector that will allow return processing only for signals that exceed a determined level. In this case, the frequency would be determined on the basis of period measurement or by frequency measurement of an oscillator that is phase-locked to the radar's amplitude gated difference signal.

The RF portion of the 35-GHz radar differs from the prototype 15-GHz radar in two ways. First, the nominal center frequency was changed from 15 GHz to 35 GHz to allow for physical size reduction. Second, the sweep range was decreased from 5 GHz to 3 GHz. This reduction was necessary since a circulator with a 5-GHz band width was not readily available. This bandwidth change will result in a slight reduction in range resolution, since resolution is proportional to sweep range in the detection method used.

It was decided to put the radar in a previously MSHA-certified enclosure used for the 15-GHz radar in order to minimize the time required to obtain MSHA certification of the radar. This decision placed special consideration upon the antenna. The radar required an RF transparent opening or "microwave window" to allow the radio frequency energy to be transmitted out of and received into the enclosure. A survey was made of the MSHA-approved optical windows that would meet the electrical requirement of a microwave window. The windows that were available are made of pyrex or polycarbonate. The polycarbonate was judged to be the more suitable, since it has been previously used successfully as the dielectric material in dielectric lens antennae. The antenna and its performance are considered to be the most sensitive part of the 35-GHz radar.

The first test of the 35-GHz radar at the MLF at Bruceton was not satisfactory in that data appeared to contain dropouts. It was determined that, at times, the radar signal return from the dielectric lens of the antenna was greater than the return from the target. During these times, the radar would attempt to measure the lens distance, since the detector has the strong signal-capture effect common to most frequency modulation detectors. Figure 3-51 depicts the strong signal-capture ratio of the FM detector. One signal was kept at constant frequency and amplitude (1000 Hz). The other signal's frequency was varied in steps. For each step, its amplitude was varied from 1/2 the amplitude of the 1000-Hz signal to twice the 1000-Hz signal. As the second signal's amplitude was varied, the detector output was recorded. In Figure 3-51, the horizontal axis is the ratio of the amplitude of the second frequency source to the amplitude of the 1000-Hz source. The vertical axis is the output of the detector. Notice that the detector output completely ignores the weaker signal when the rates are greater than two.

Analysis of the radar return signals showed the frequency generated by the lens return was approximately 300 Hz. The radar has a bandpass filter prior to detector consisting of a four pole-high pass at 1000 Hz and a two-pole-low pass at

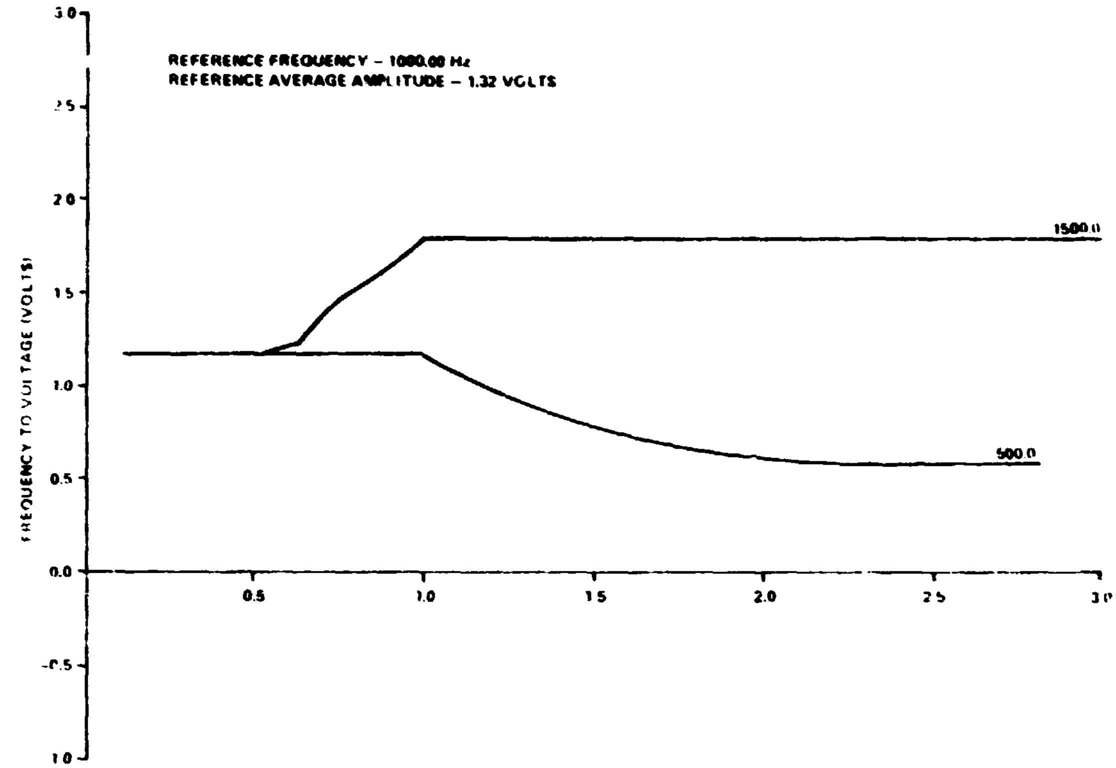


Figure 3-51. Frequency/voltage versus frequency/average amplitude.

5000 Hz. The four-pole-high pass section was changed to an eight-pole configuration to obtain a larger reflection of the 300-Hz signal. A second test of the radar was performed at the Bruceton MLF facility with the modified filter. This test was considered very successful.

The horizontal axis of the graph in Figure 3-52 is the down-face distance of the coal cut test block. The vertical axis is the output of three different sensors measuring approximately the same roof profile. The top trace is from the acoustic sensor, the middle trace is from the 35-GHz radar, and the bottom trace is from a mechanical follower. For all practical purposes the traces are identical except at the 60-ft mark. At this point, the roof had a slab of styrofoam to simulate a void (represented by a change in density). Because of the low loss and low dielectric constant of the foam, the radar measured through the foam. Recent tests of a second radar conducted by Foster-Miller Associates, Inc., at the MLF facility produced the same results (Fig. 3-53).

Neither of the modified 35-GHz or 15-GHz configurations were found to be satisfactory; both were subject to signal drop-out when tested under water spray and dust conditions at the Bruceton mock longwall test facility. In view of the environmental conditions that interfere with the continuous measuring capability of the radar, it cannot be used as a primary cut follower within the vertical control system.

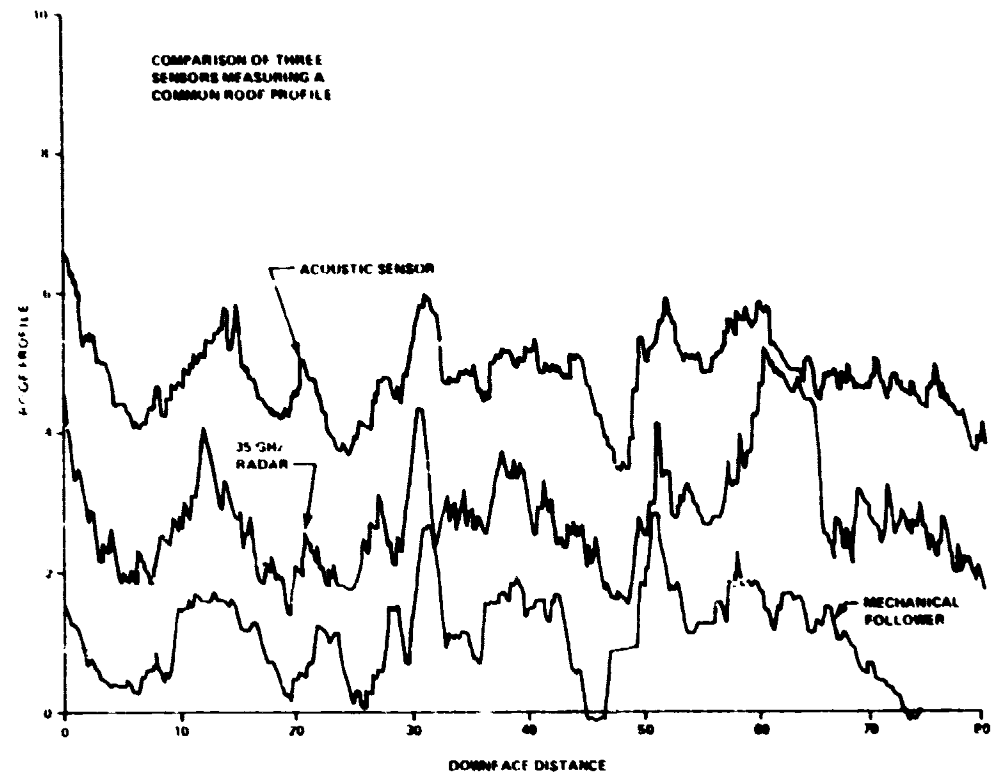


Figure 3-52. Roof profile measured by acoustic, radar, and mechanical sensors - Bruceton test.

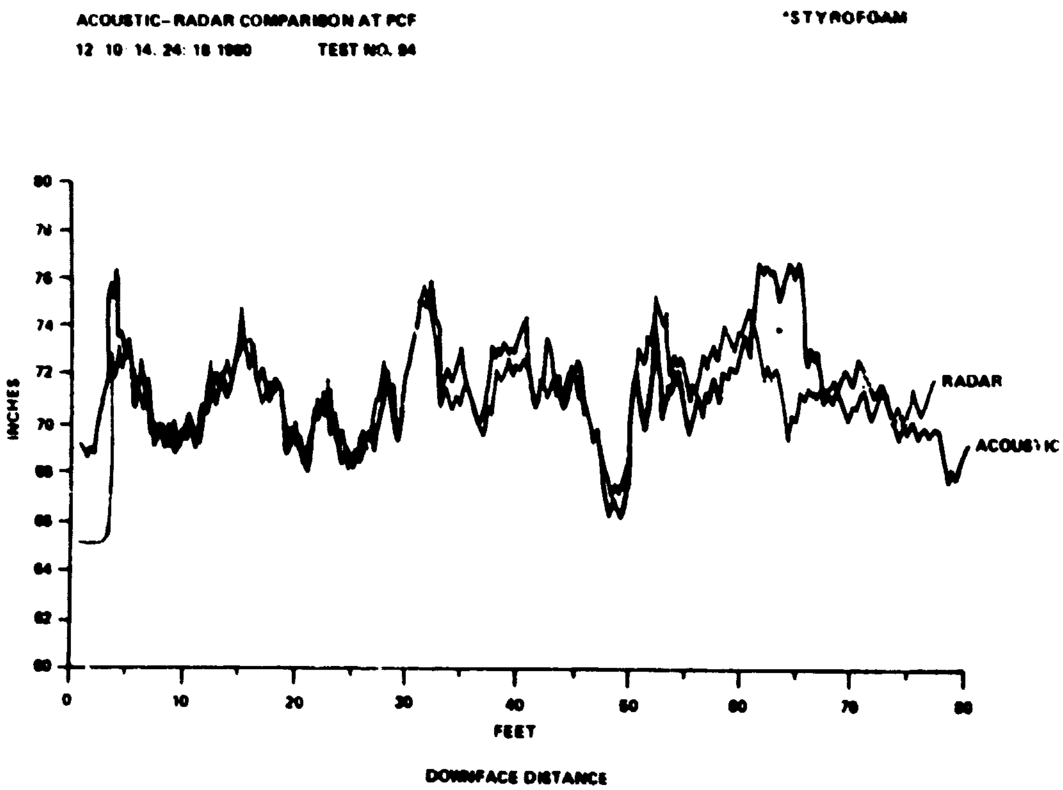


Figure 3-53. Comparison of acoustic and radar profiles.

3.2.2 Acoustic

Foster-Miller Associates, Inc., procured a commercial transducer from the Industrial Systems Division of Wesmar in Seattle, Washington, and adapted it to the measurement of the excavated coal seam's profile. The signal from the transducer is directed along the horizontal axes, striking a deflector plate which rotates the signal 90 degrees and directs it upward to the roof. The return signal follows the same path and is picked up by a receiver.

Initial tests at the Bruceton mock longwall facility (MLF) were satisfactory, measuring the roof profile to an accuracy of ±1/2 in. (Fig. 3-54). This configuration of the acoustic sensor with the 45 degrees deflector plate and high signal power level (as compared to the radar) was found to be insensitive to the dust and water sprays present during MLF tests.

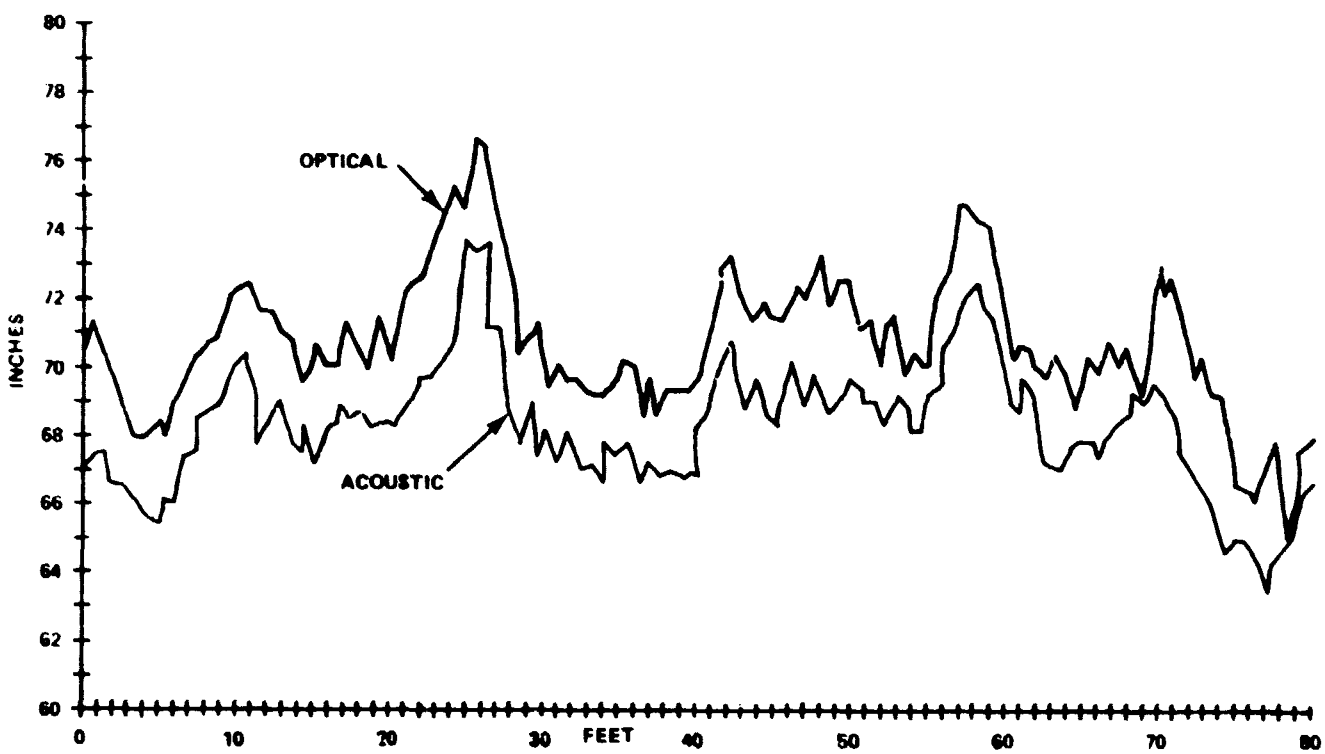


Figure 3-54. Comparison of acoustic and optical cut followers.

This acoustic follower is well suited as a distance measuring device: It is commercially available and relatively inexpensive; it is durable and reliable, does not require extensive signal processing, and is unaffected by extraneous acoustic sources. It also has the advantage that it measures an average distance to an irregular surface, thereby avoiding the rapidly and constantly changing signals which can result from a rough surface if the sensor's resolution is too great.

3.2.3 Optical

The optical cut-follower, Figures 3-55 and 3-56, was developed by Scientific Applications, Inc., of Huntsville, Alabama (NAS8-33700), with technical support from Adjunct Systems, Inc. It operates on a triangulation concept in the following manner.

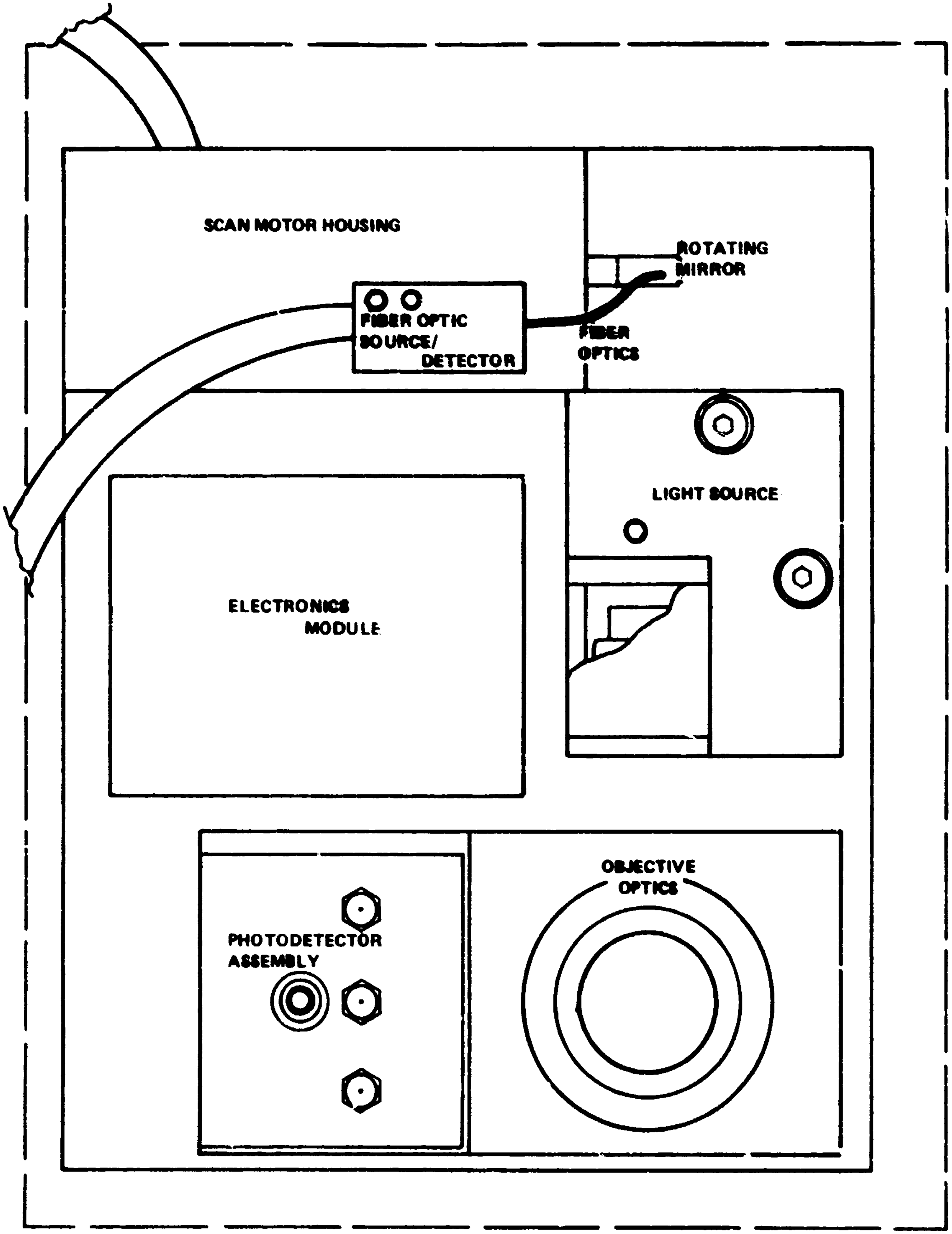


Figure 3-55. Optical last cut follower, top view.

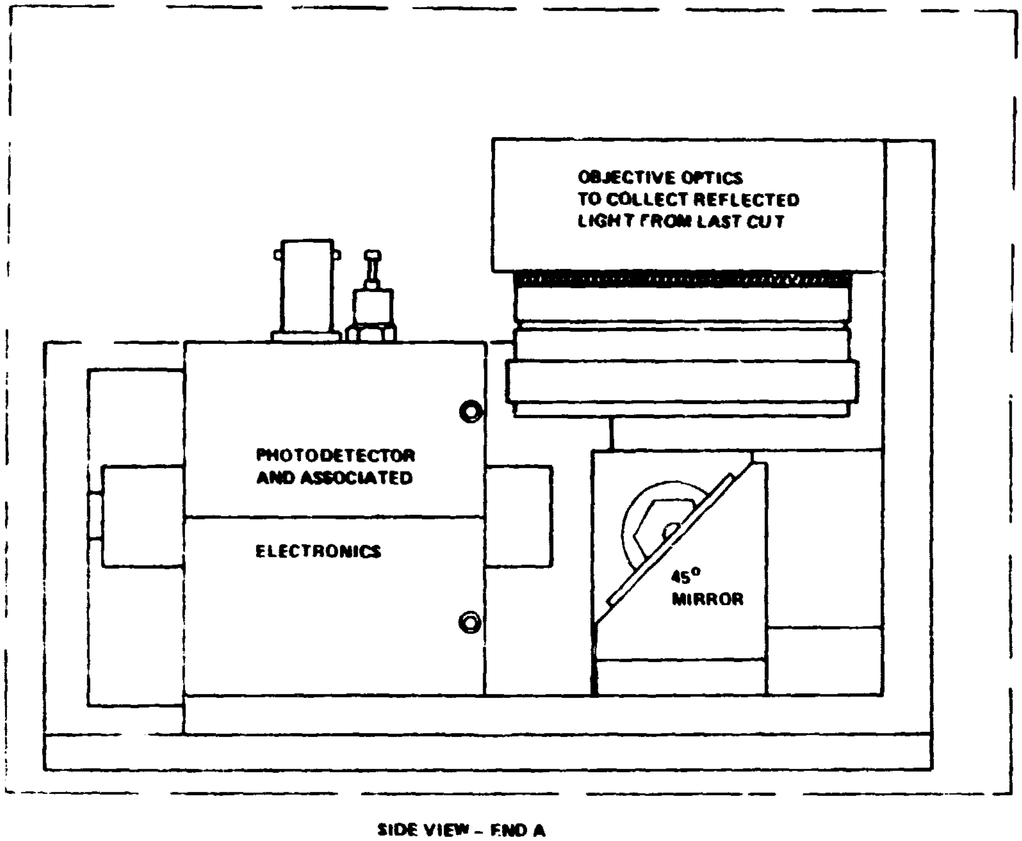


Figure 3-56. Optical last cut follower, side view.

An objective lens images the last cut onto a focal plane where a narrow slit is affixed to a photodetector and placed to limit the field of view to a small slice across (transverse to) the last cut and directly above the device. The field is as close to the shearer's cutting drum as practical

An incandescent light beam (from a miner's lamp) is reflected from a rotating mirror mounted 15.24 cm from, but at an equal elevation to, the principal plane of the objective lens. The light beam is reflected from the mirror toward the roof so that the light beam scans along the surface of the last cut as the mirror rotates. When the beam falls within the field-of-view, the photodetector responds with an output electrical pulse.

The rotating mirror is equipped with an incremental optical shaft rotation encoder, designed to produce 2,000 pulses per revolution. At a pre-set point in the mirror's rotation, a counter is activated (Fig. 3-57). The counter continues recording pulses until a pulse is received from the photodetector indicating the instant the light beam has crossed the field-of-view. Trigonometric relationships allow the computation of the last cut height above the objective lens. This distance, added to a constant associated with the offset in vertical and horizontal between the objective and the center of the cutting drum, provides the height to the last cut. A functional schematic of the optical last cut follower is shown in Figure 3-57.

The electronic system does not use a microcomputer to perform the trigonometric calculation. Since the total number of resolution elements over the complete range of operations is only 4(45 - 17) = 112, and the relationships are constant for any given

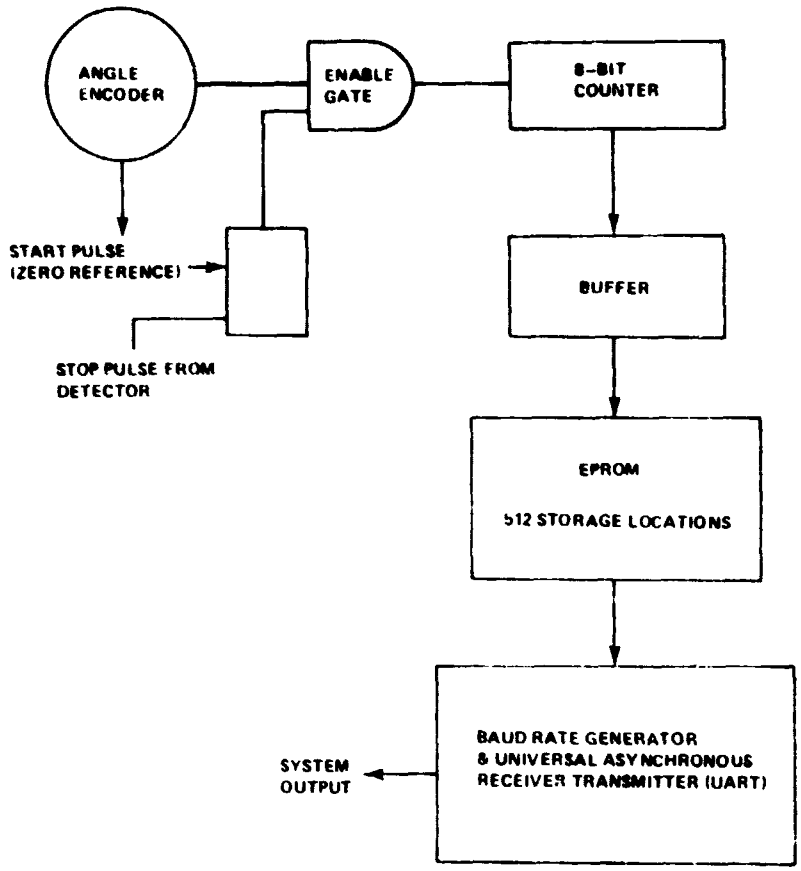


Figure 3-57. Functional schematic of converting process and transmitting electronics.

height, the answers associated with each count can be pre-stored in a "read-only" memory. Therefore, the system need only rotate the mirror until the beam is detected, at which time the encoder count is used to address the memory, extract the answer, and condition it for transmission to the controller.

The instrument, weighing 45 lb, is housed in an explosive-proof box, measuring 6 in. by 5 in. by 10 in., and is mechanically and electrically compatible with the mounting connections used for the radar cut-follower.

The measured performance (Fig. 3-58) indicates a 1/16-in. accuracy.

The instrument has also been tested at the Bruceton mock longwall face, mounted on the Joy longwall shearer.

The results of the Bruceton tests are shown on Figures 3-54 through 3-59 depicting the roof profile measured while the Joy shearer was cutting. The curves are displayed with an accompanying acoustic measurement (offset) for comparison. Notice that the optical curve follows the acoustic curve with a surprising degree of accuracy. Also, some dust buildup was observed on the surface of the optical lens during cutting. Means of resolving this problem are under investigation.

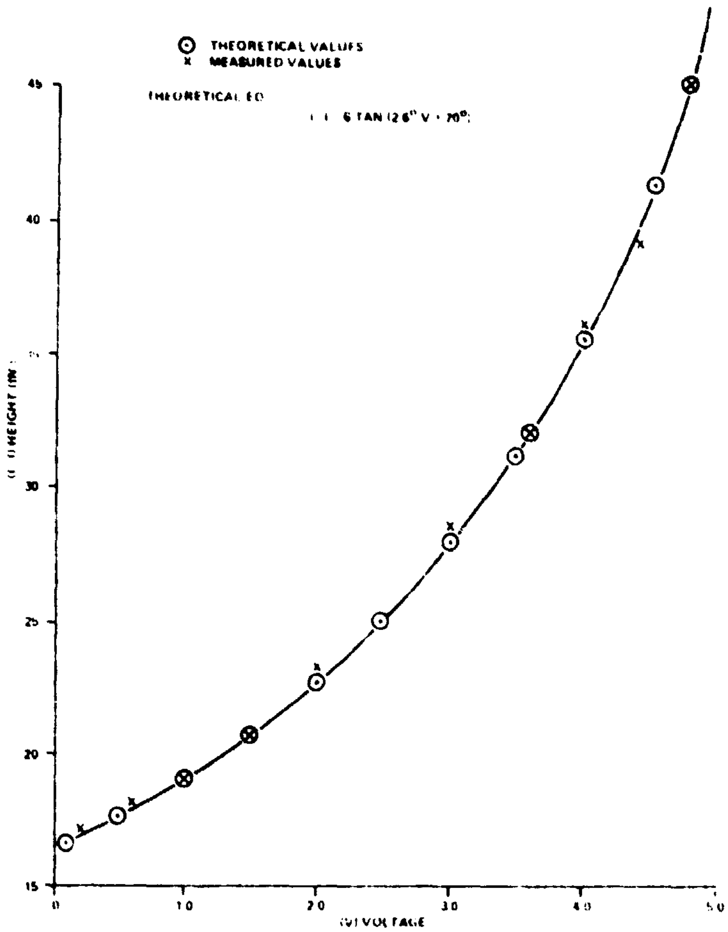


Figure 3-58. Acceptance test results, optical cut follower.

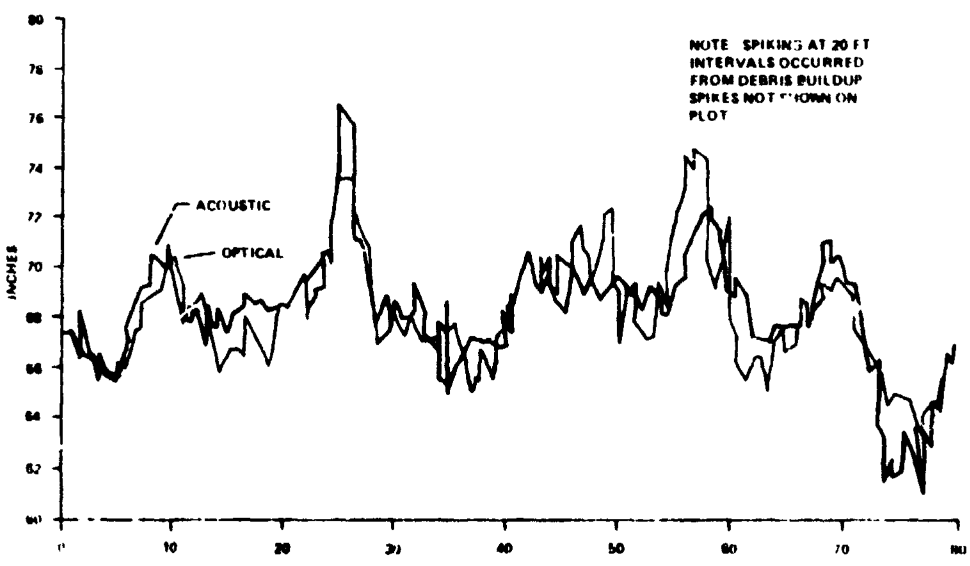


Figure 3-59. Comparative test results, optical and acoustic cut follower.

4.0 GUIDANCE AND CONTROL STUDIES

Section 2.0 gave a description of the guidance and control problems and then went on to indicate the solutions that evolved. Before these solutions were adopted, however, they were analyzed exhaustively by mathematical modeling, computer simulation, and hybrid simulation at the Bruceton mock longwall face (MLF). Although fullscale automatic control of the horizon has not yet taken place underground, there is no doubt that the performance will be acceptable. This statement is based in part on the simulation that has been done over a period of several years, but mostly on the tests of sensors done underground, principally the Natural Background Sensor (NBS) and the sensitized pick.

The simulations have included all parameters which could influence the guidance and control of the drum, and they have had Monte Carlo simulations where applicable. One such parameter that indisputably holds a central position in this respect is the geometry of the boundaries of the coal seam, i.e., the coal/rock interfaces. Are the average curvatures of the surfaces sufficiently small that it makes sense to speak of a sensor tracking the interface and thereby affecting the control of the drum? Are the roof and floor interfaces closely related to one another in terms of parallelism and correlation? The answers to these and other geometrical questions were found by statistical analyses of raw data obtained from measurements of the profiles of several mines. The answers can be summarized thus: The floor and roof interfaces are generally parallel to one another and undulate in unison [14], and the curvature is generally small enough that it is reasonable to speak of a sensor making measurements in order to control the roof drum. And in the control of the floor drum, the roof and floor surfaces are sufficiently correlated so that adequate floor drum control can be achieved by controlling the floor drum to be a constant height from the roof drum cut. These statistical characterizations of the interfaces were incorporated into computer programs so that simulation could be realistically accomplished. Generally, the simulation included the following features:

a) Detailed modeling of the mine geometry including actual interface profiles and techniques for generating statistically similar coal/shale interface profiles from a given initial profile which is used to give realistic results when multiple passes are made.

b) Detailed geometrical model of the shearer including its location along, and orientation with respect to, the face.

c) Technique for determining the actual track that would result when laying 5-ft conveyor sections along a roughly cut bottom.

d) Detailed non-linear representation of shearer actuator dynamics including the hydraulic coupling between the two ranging arms.

e) Detailed representation of the nucleonic and natural radiation coal interface detectors, including the nonlinear calibration curves, Poisson distributed sensor noise, and air gaps.

f) Complete representation of coal/shale presence sensors, including a probabilistic representation of their correctness.

g) Complete representation of last and present-cut followers.

h) Modular hierarchical control law algorithm that is able to accommodate a variety of sensor complements and control law implementations.

In computer simulations like these, the hypothesized sensors and their locations are just that: hypothetical; and the configurations are guided by, but do not necessarily conform to, totally realistic requirements. More realism was introduced by actually using a shearer located on the mock longwall face at DOE's Bruceton facility. The composition of the longwall block-cap of cement – simulated coal of a mixture of crushed coal, cement, and fly ash – proved to be satisfactory for many of the tests, although there was a tendency for the artificial coal to be milled rather than fractured, the observed process that generally takes place underground. In the tests of the sensitized pick on the MLF, it was found that the pick showed little difference in strain when striking the cap and artificial coal.

The tests on the Joy machine represented an instance where the entire horizon control of both drums of the shearer was under computer control. Because of the thoroughness with which the investigations on the sensors and their characteristics had been carried out, as well as the thoroughness with which the computer simulations had been done, the mechanization of the shearer was relatively straightforward. Tests were carried out using, in various applicable combinations, the sensitized picks, mechanical, electromagnetic (radar and visible light), acoustic followers, and a down-face distance sensor. Tests were also conducted where the shearer trammed but no coal was cut; these tests, which did not involve the sensitized picks, saved the coal face, but at the same time, incorporated the shearer geometry and dynamics.

5.0 FACE ALIGNMENT SYSTEM (FAMS)

5.1 Angle Cart Development

The yaw and roll planes were to be controlled by the face alignment system, the second major control system defined during the longwall shearer guidance and control development.

Details of this development are to be found in the MSFC progress reports [12], as well as in Bendix reports [9], and in the Benton Corporation reports [19, 20].

After the idea of using a directional gyroscope was discarded, the concept for face alignment measurement had its origins in observing that the forward movement of the shearer was constrained by a sequence of tracks or pans forming a flexible path along which the shearer rode. The pans were pushed forward as the chocks or roof supports were moved, following the shearer's passage along the face. Movement was halted when the pans encountered the new coal face. Thus, the pan line itself reflected the azimuth of the face. Any obstruction – large steps in the floor, large rocks, or coal – could stop the forward pan movement prior to its encountering the actual coal seam's exposed surface, causing a faulty alignment of the pans and, hence, an uneven cut by the shearer. However, if the space between the coal seam and forward pan line was smooth and contained no major obstructions, the proper alignment of shearer and seam surface was attained. Thus, the idea of using the pan line as a measure of alignment was evolved.

Mathematically, the procedure was trigonometric. Knowing the two end points at the headgate and tailgate, measuring the angles formed by adjacent 5-ft pan sections, and knowing the distance from either reference point from which these angular measurements were made, an actual trace of the pan line, hence the contour of the coal face, could be plotted. For automation, the computer used to process the data collected could command each, or a group of, roof supports to advance and execute a "dress-right/left-dress" command. This metered movement was possible by control of the hydraulic pressure that activated the rams which pulled the chocks forward.

The initial step was to set up a laboratory test by which the feasibility of the idea could be tested (Fig. 5-1). Results of the laboratory tests (Fig. 5-2) were encouraging and led to the decision to redesign the instrument for testing at the mock longwall facility in Bruceton using the Joy shearer. A design and fabrication contract (NAS8-33209) was awarded to the Benton Corporation for test hardware that could be appropriately mounted on the Joy shearer. The test results (Fig. 5-3) were satisfactory, proving that the concept did in fact measure the alignment of the pans satisfactorily. However, the location of the equipment on the rear of the Joy shearer was not satisfactory for use on an operating face. Thus, the equipment was relocated and integrated into the center body section of the Joy shearer (Fig. 5-4). Retesting of the reconfigured hardware produced unsatisfactory results arising from the shearer's forces bearing upon the unsupported vertical portions of the pan sections (Eicotrack) and distorting the plane of reference. Design modifications were initiated which, in essence, eliminated the skids that moved along the surface of the Eicotrack, replacing them with channels that caped the rack. This arrangement eliminated distortions arising from the irregularities of the vertical surface introduced by stresses from the shearer's drive mechanism. The configuration was designed specifically for integration into an Eickhoff 300L shearer, since it was found to be the type most commonly used (Fig. 5-5). The mini-hardened hardware is shown on Figures 5-6 and 5-7.

Figure 5-1. Laboratory version of face alignment measuring instrument.

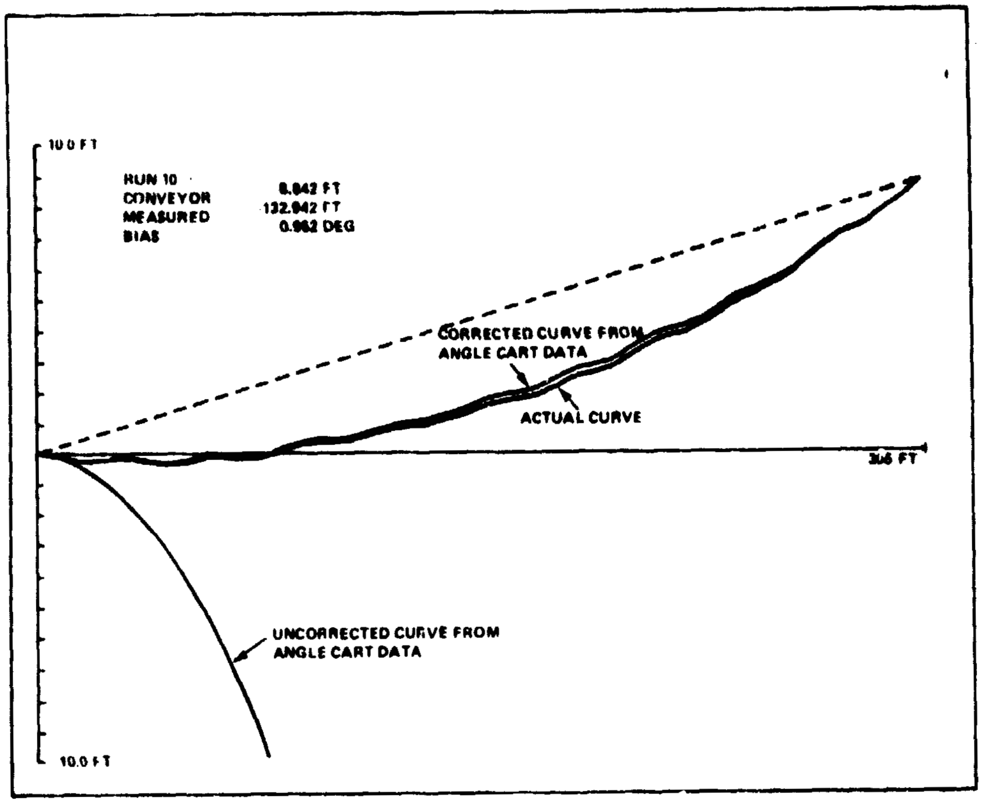


Figure 5-2. Yaw measurements, simulated coal face measurement.

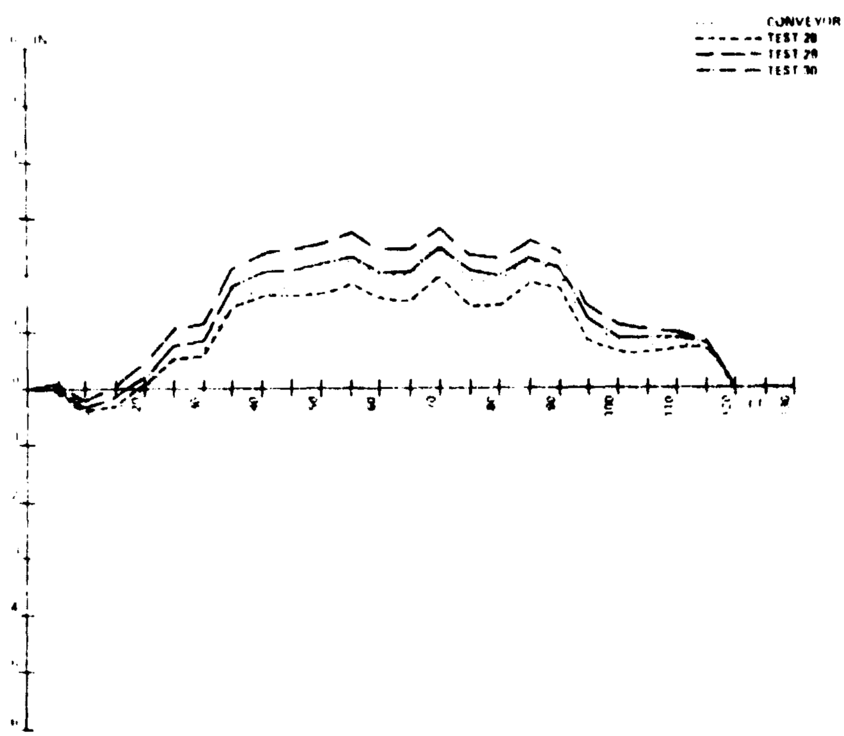


Figure 5-3. Face alignment measurement, Bruceton test results.

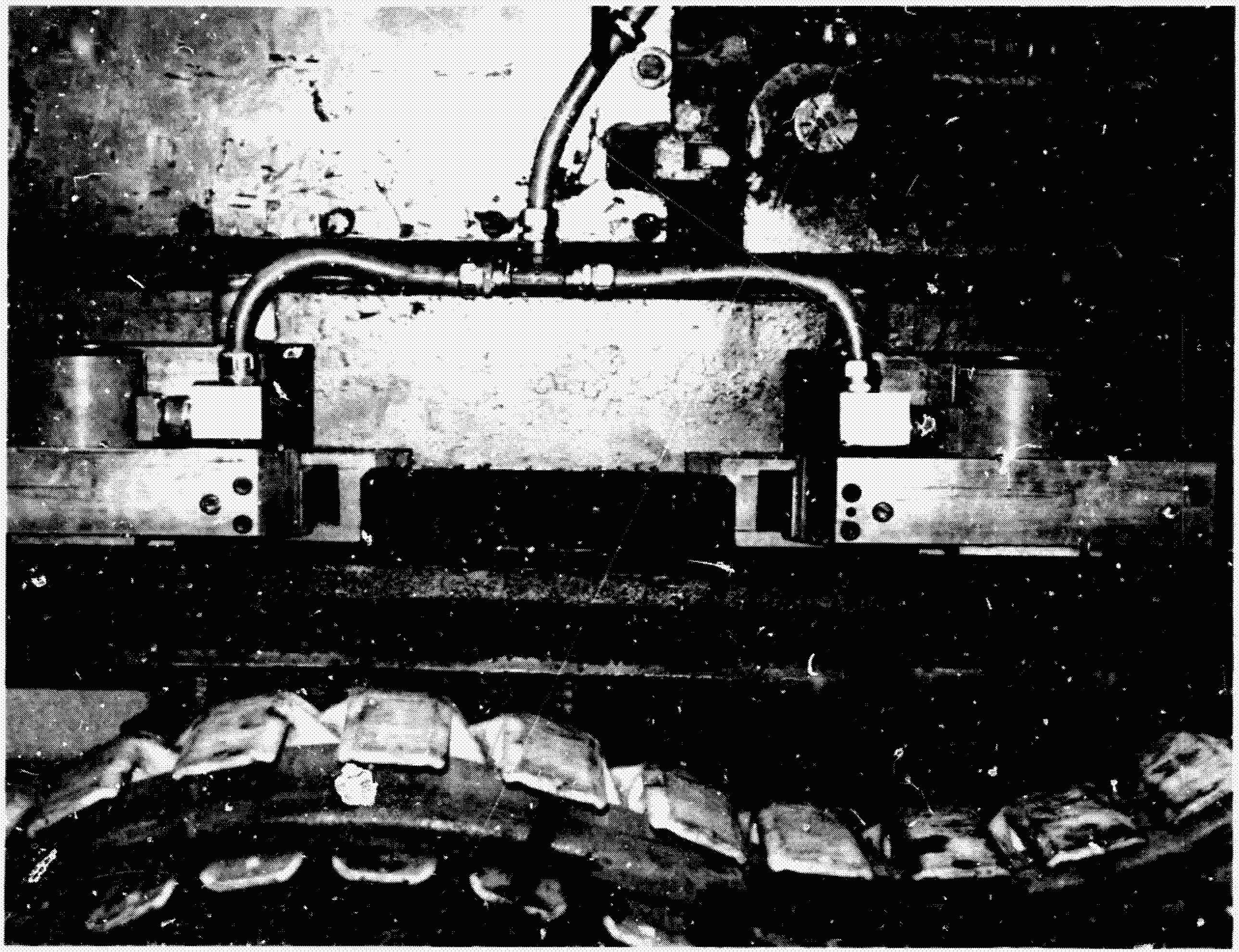


Figure 5-4. View of face alignment measuring unit mounted on a Joy shearer.

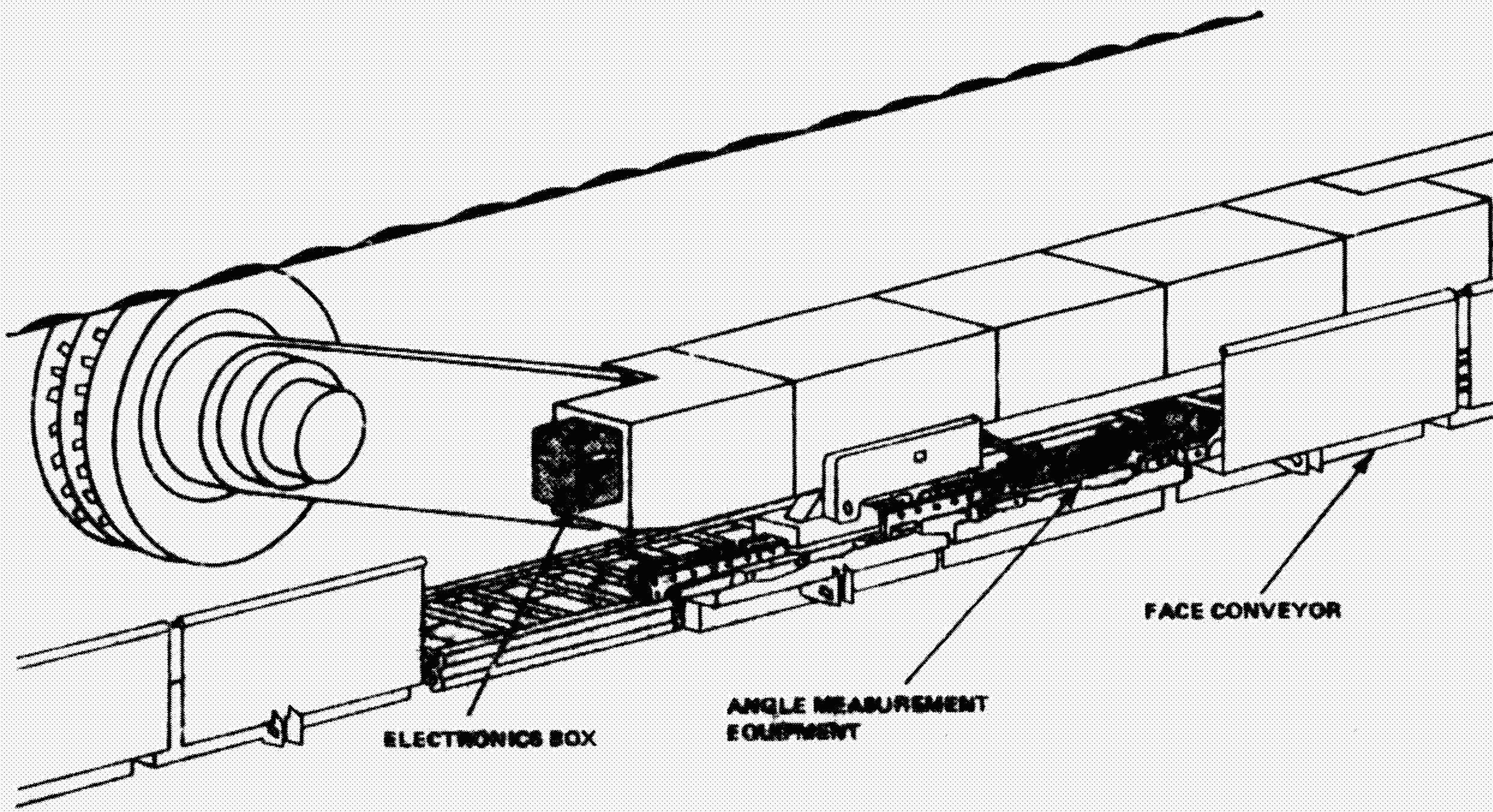


Figure 5-5. Coal face measuring system, location on an Eickhoff shearer.

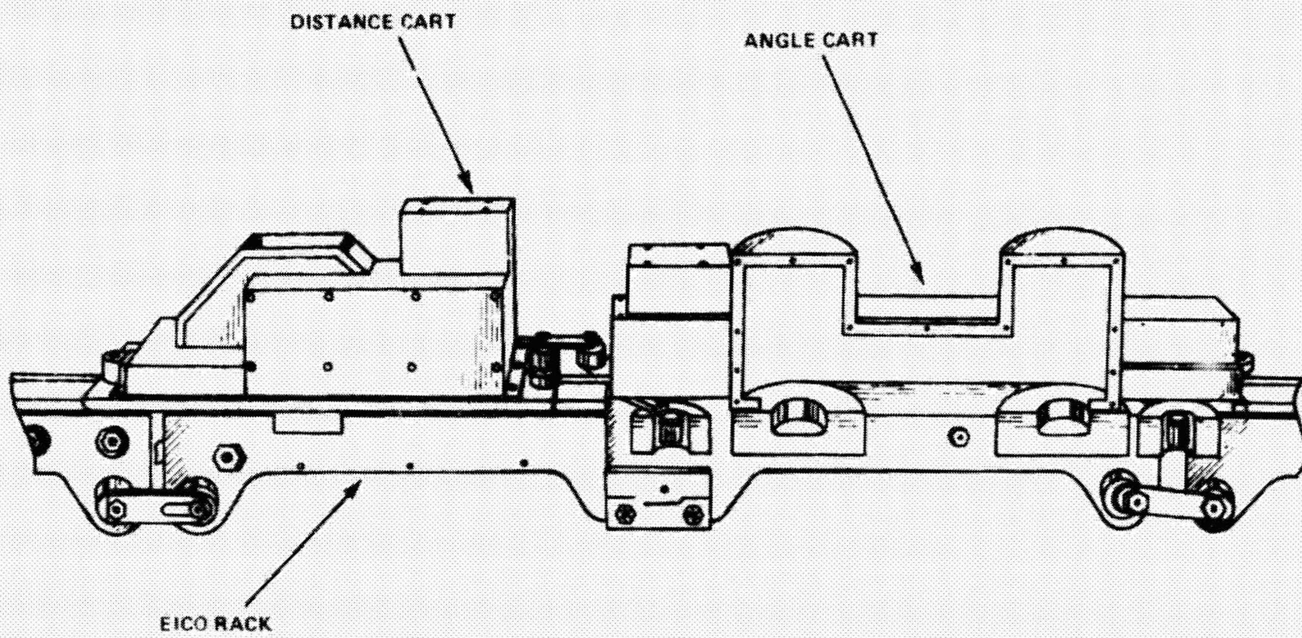


Figure 5-6. Angle and distance transducer.

This configuration was tested at Bruceton and found to measure pan alignment to an accuracy of ±1 ft in 500 ft; since the design requirement was ±3 ft in 500 ft, the instrument was accepted (Fig. 5-8).

The electronics subsystem, including a display panel, was designed for location at either end of the body of the shearer for operator convenience.

Two sets of hardware were fabricated, one for aboveground test and checkout at Bruceton and one for underground testing. The Bruceton unit was intended to serve as a spare, as well as for "trouble-shooting" purposes during the planned underground test operations.

Underground testing responsibility was assigned to Foster-Miller Associates, Inc., who in turn subcontracted test operations to the Benton Corporation. A coal mine, the North American Coal Company's mine in Darlington, Ohio, was located; and agreements for test operations concluded with the mine operators. During the period between the time the agreement was concluded and preliminary integration investigations were initiated, it was determined that the operator had modified his shearer. These modifications essentially eliminated machine/FAMS integration compatibility and negated the planned test series. Scheduling problems were encountered when relocation to another coal mine was considered, forcing the decision to defer underground testing to the Department of Energy at some future date.

5.2 The Optical Alignment Measurement Instrument

In view of the fact that the angle cart system was machine-dependent, an alternate method to measure face alignment was investigated [21]. While initial design considerations envisioned the use of a laser beam as a reference, schedule considerations required a change in approach to one that allowed adequate time for

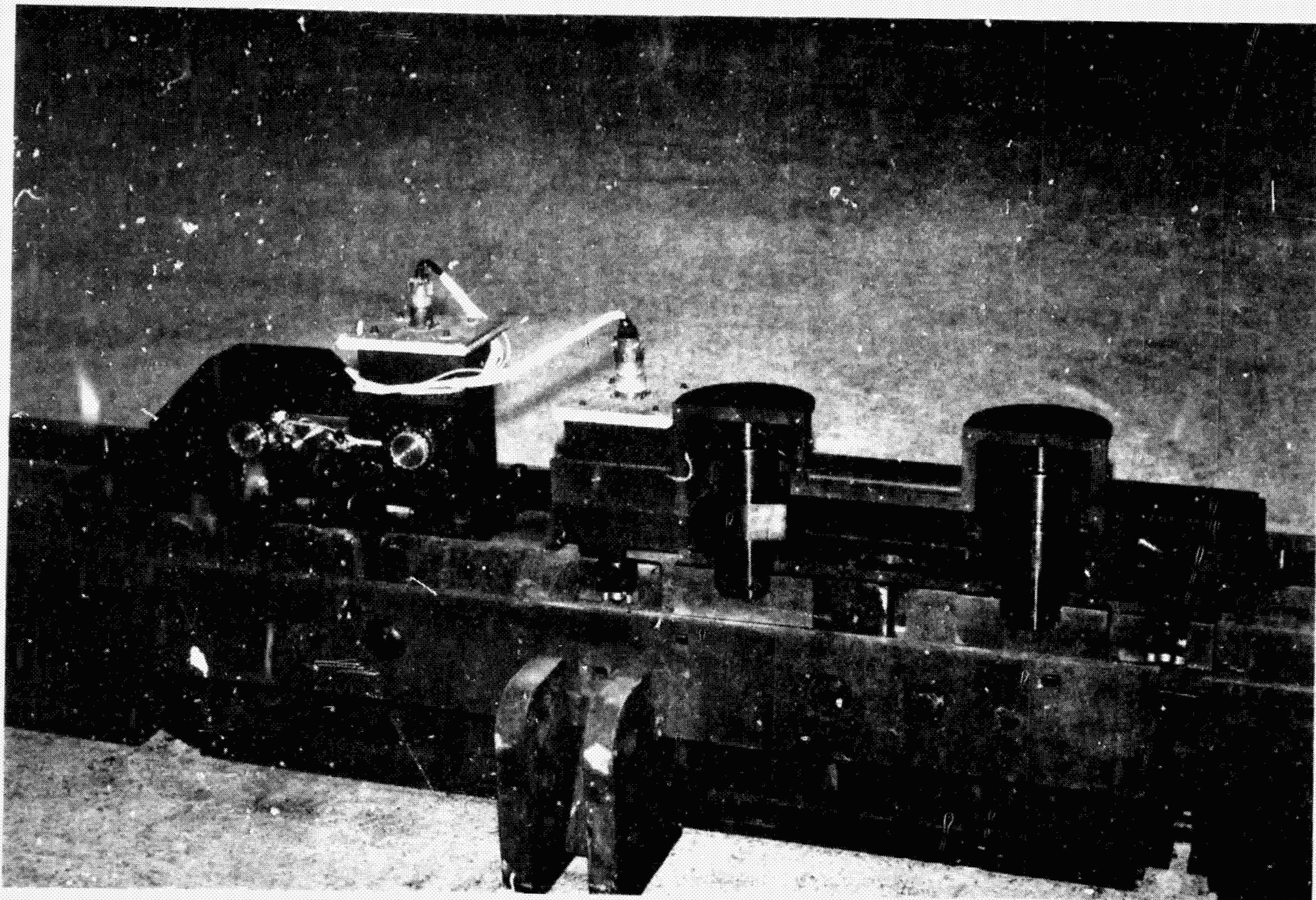


Figure 5-7. Internal view of face alignment measuring system on an Eicor ck.

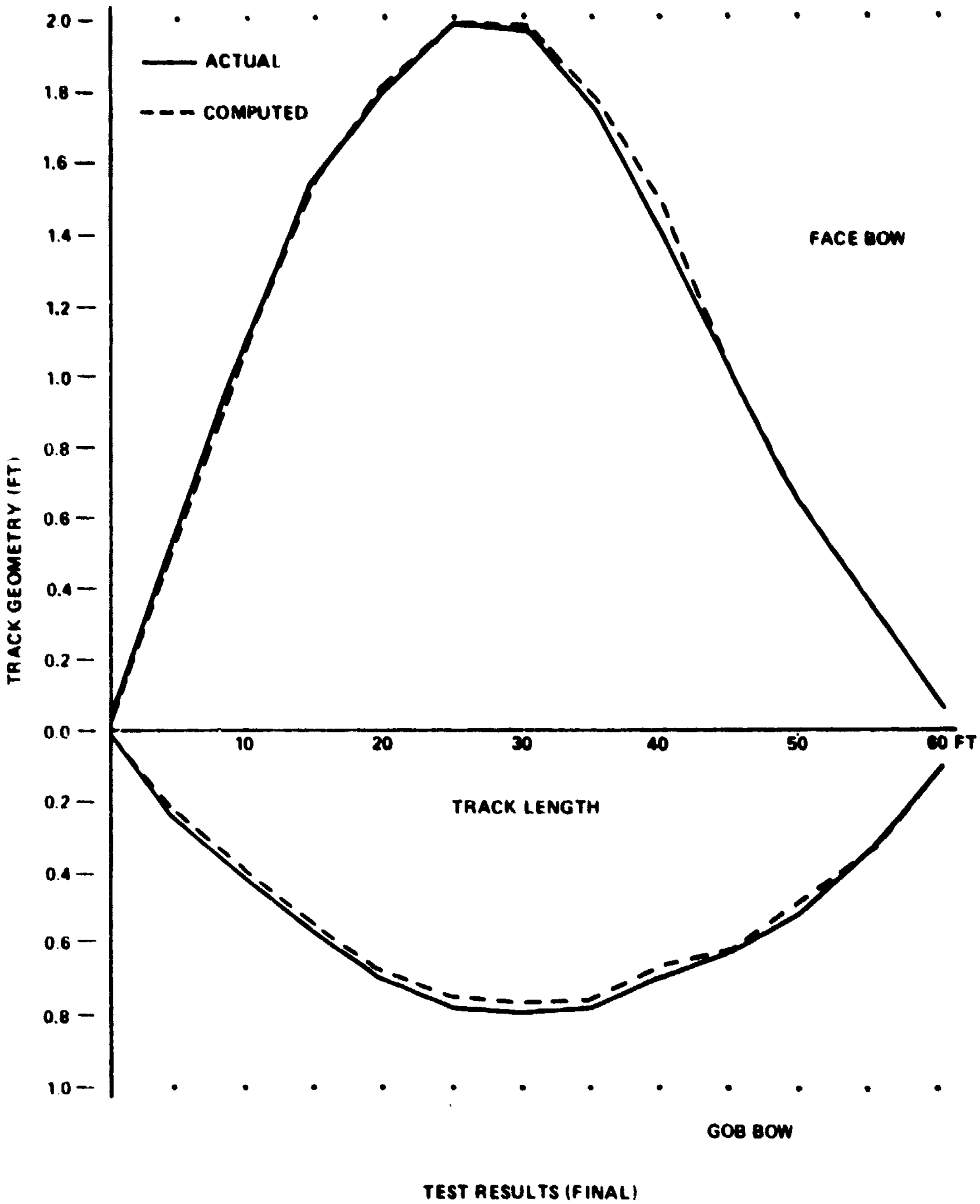


Figure 5-8. Face alignment measuring test results.

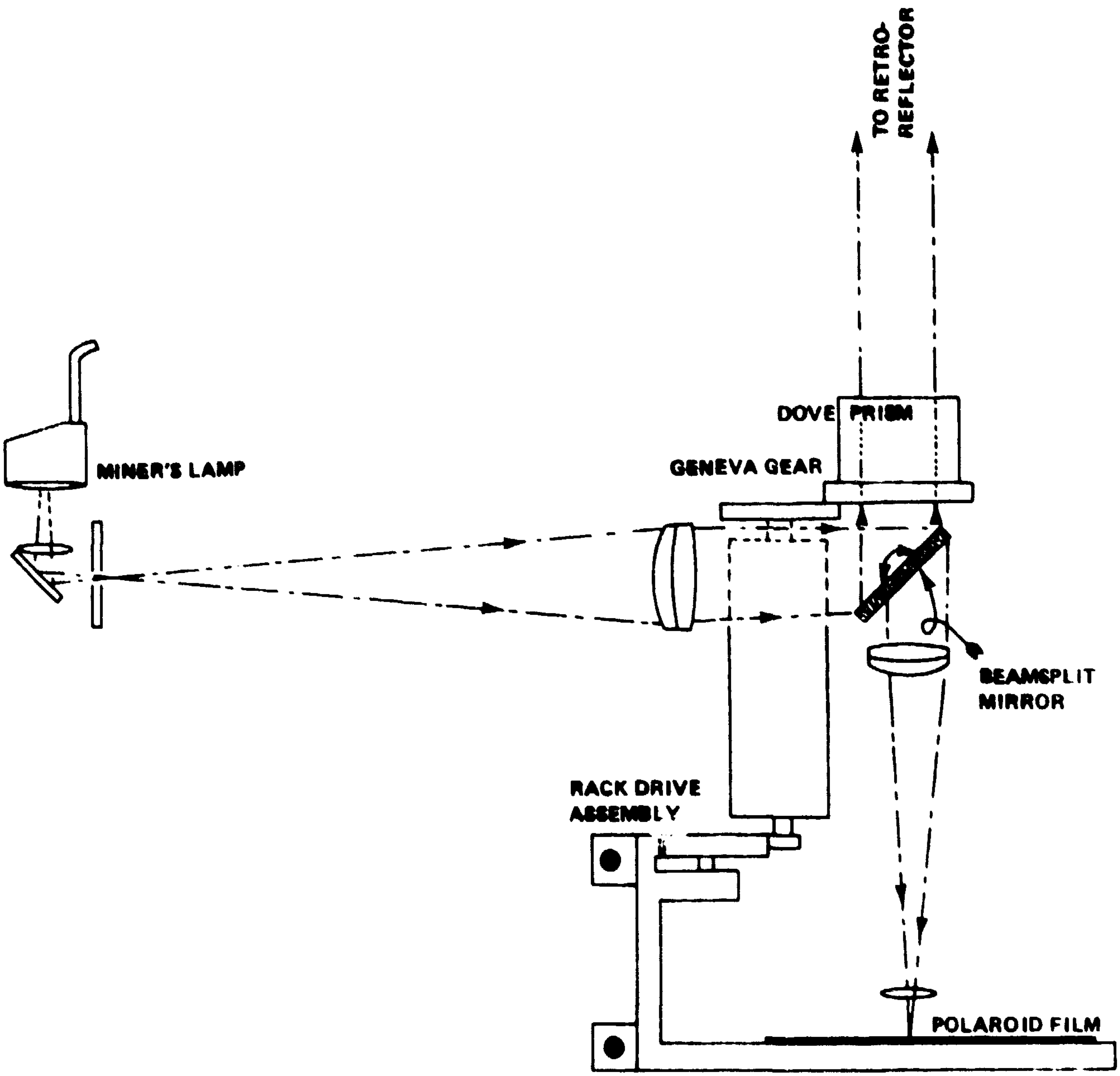


Figure 5 9. Schematic layout, optical alignment instrument.

in-mine testing on an operational longwall shearer. The time element ruled out any equipment that would require MSHA certification. Using the light from a miner's lamp as a reference, dove prisms to transform measurements to two planes, a mechanical drive mechanism, and a film on which the signals would be recorded, an alignment instrument was assembled. The signal reflected from the shearer by a retroreflector mounted in a housing that rode along the rack, producing periodically interrupted return signals that were recorded as "points" on the film (Figs. 5-9 and 5-10). The film record is shown in Figure 5-11. Photographs of the actual hardware are shown in Figures 5-12 and 5-13.

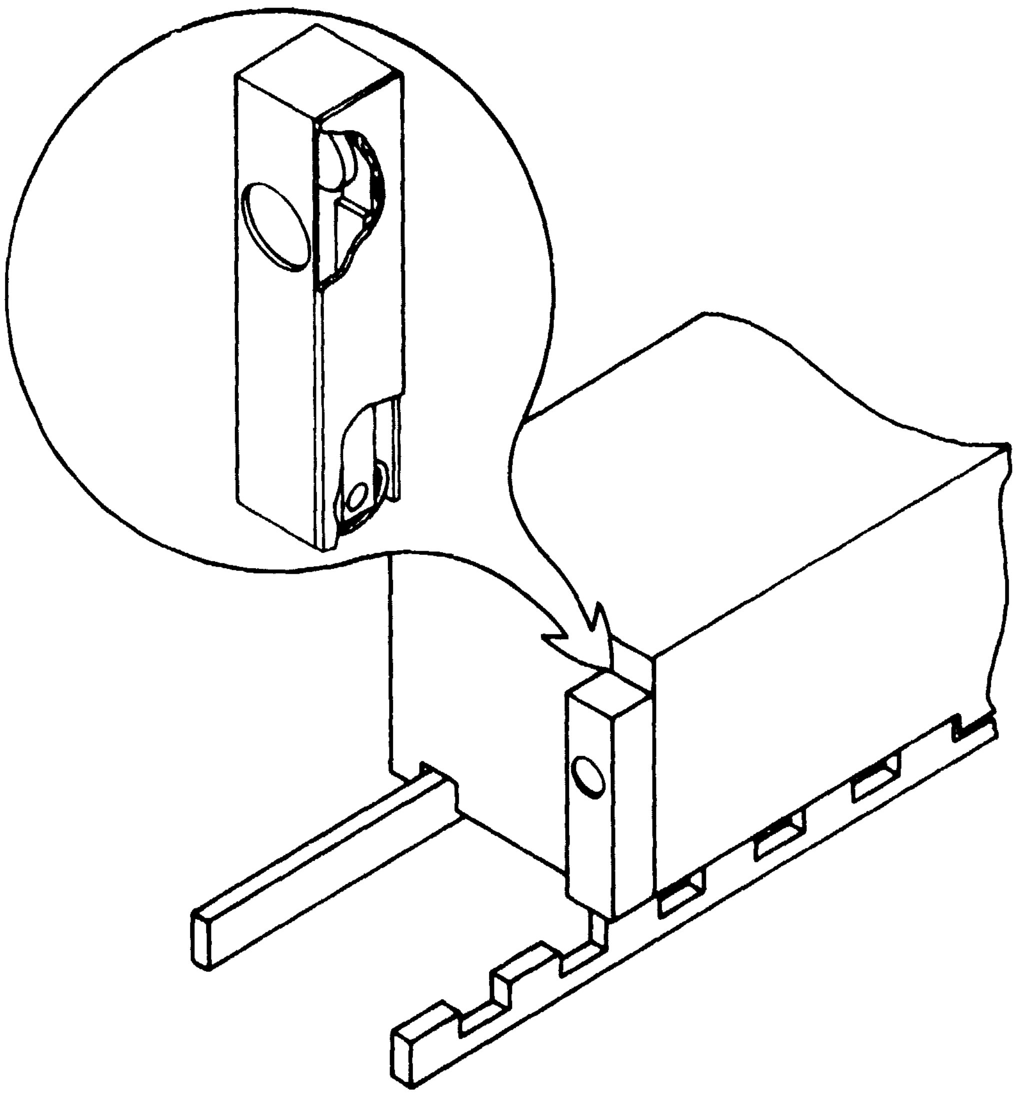


Figure 5-10. Retroreflector housing, optical alignment measuring system.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

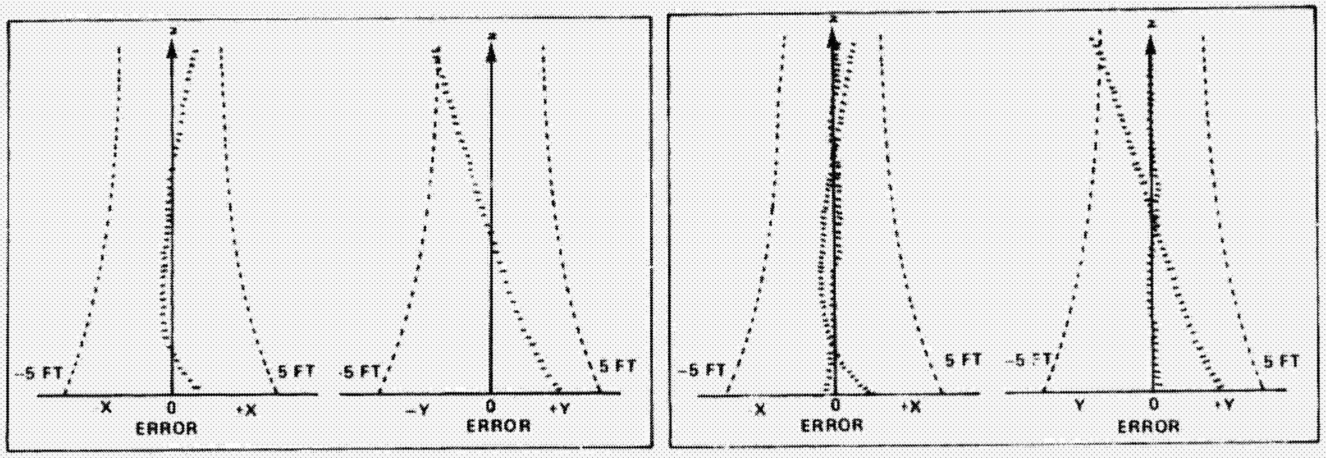


Figure 5-11. Overlay of new "XY" and "YE" trajectories, optical alignment measurements.

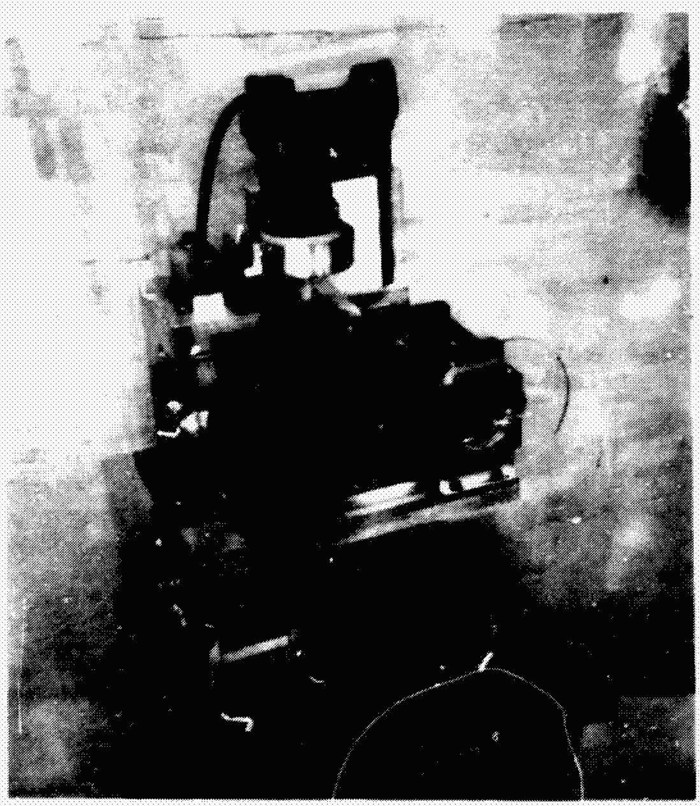


Figure 5-12. Optical alignment measuring instrument, internal arrangements.

Figure 5-13. Retroreflector housing.

An actual in-mine test was performed at the Jim Walters No. 3 mine in Adger, Alabama, during August 1981. The instrument [21] successfully measured the alignment up to 300 ft, at which distance the machine rounded a bow in the face and the signal was lost. Sufficient data was accumulated to prove that the concept of an optical alignment measuring system was feasible and that, with redesign of the instrument as proposed [21], a practical device for measuring alignment could be obtained.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Vertical Control System

Begun in 1975, when relatively little was known about the possibilities of automatically controlling the shearer, the program has advanced to the point where many of the 1975 unknowns are now known. Many approaches to the automation problem, including guidance and control schemes, that appeared promising in 1975 has been abandoned after thorough investigation showed that, even though in principle they could be made to work, in practice, they were not feasible.

As the program progressed, it became apparent that the horizons of the drums could be automatically controlled by sensors and a computer and, in most cases, more efficiently than by a human controller acting alone. Inasmuch as this program was investigating a new concept, the above conclusion was not the result of lowering an aim, but was rather the conclusion demanded by the technological, economic, and physical constraints.

A necessary part of this program was to determine present manual practices and to evaluate the user's interest in automatic horizon control. There was almost always an interest in the aims of the program; but, more often than not, there was a special interest in some aspect of the program. For example, there are several instances where the coal falls away freely from the roof, and there is no need for a sensor to detect the roof being struck; but the operators have trouble controlling the elevation of the floor drum. In these cases, they are interested in a subsystem of the entire system. The system has evolved so that a selection of sensors, which can accomplish a particular job, can easily be used. In other words, if an operator wants to control the roof drum only, a package is available to him, e.g., a computer, a natural background sensor, an acoustic distance sensor, and an arm potentiometer. At this point, control can be done one of two ways: automatically, with the computer issuing commands to the drum; or manually, with the computer furnishing instructions to the operator. Because of the ease of implementation, there has been wide interest in the latter approach, an approach which entails minimum interface with the shearer and is somewhat easier to install. If this requirement were apt to be common, then a computer with somewhat less capability, and consequently cheaper, could be used. This requirement led to the development of the display/processor using a hand-held programmable computer described earlier. On the basis of this observation, it was concluded that future work in the automation area should place adequate emphasis on the operator-assisted mode in order to meet the particular requirements of a mine. Below are listed the sensors, and a precis of their characteristics, which have been retained; followed by the sensors which were rejected.

6.1.1 Sensors Retained

6.1.1.1 Natural Background Sensor (NBS)

The NBS enjoys an accuracy which is ample for horizon control. Accuracy is selectable in that it depends on the chosen crystal size and on the duration of the count: the longer the count, the higher the accuracy. Processing of the counts and conversion to thickness, or to an error signal, are straightforward. Tests of the NBS have shown it to be reasonably rugged, but care must be taken to control the humidity. Cost of the NBS is reasonable.

6.1.1.2 Acoustic Distance Sensor

This sensor has excellent accuracy (approximately ±1 in.) and is relatively inexpensive, since it uses a unit which is being applied commercially. It is immune to outside disturbances, but instances have occurred where the entire unit has been dislodged from its location because of falling debris. However, it is believed that it can be adequately protected.

6.1.1.3 Sensitized Pick

Extensive statistical analysis of in-mine tests show that, for the combinations of coal and rock tested, the sensitized pick can distinguish between coal and rock a usably high percentage of time. This percentage can be increased by increasing the amount the sensitized pick extends above the normal picks. Two approaches are available in terms of supplying power: the pick and mounting block are self-contained, with the mounting block containing a battery and a transmitter; or power is fed and information received by means of slip rings.

6.1.1.4 Downface Distance Sensor

A multi-turn potentiometer provides suitable accuracy.

6.1.1.5 Arm Potentiometer

This is a standard potentiometer and presents no problems.

6.1.2 Sensors Which Were Rejected or Need Additional Work

6.1.2.1 Nucleonic Sensor

This sensor uses a radioactive source for gamma rays and a sodium iodide crystal to detect them. For acceptable accuracy, it requires no air gap between the coal surface and the surfaces of the source and detector; otherwise, errors incurred by the unimpeded flow of photons through air are unacceptably large. The requirement of physical contact with the coal surface and the impracticability of obtaining a sealed contact render this sensor almost useless for practical dynamical applications. Having to contact a surface in relative motion makes it subject to damage. Also, having a radioactive source might tend to cause uneasiness on the part of the operators. No additional work is recommended on this sensor.

6.1.2.2 Radar Depth Sensor

A large effort was put into measuring coal depths using both CW-FM and monocycle radar. The conclusion finally drawn was that, for the accuracy desired, coal attenuates electromagnetic waves too much for the waves to have appreciable penetration. Furthermore, the difference in the dielectric constants of coal and shale is too small to allow a large reflection back from the interface of the two. Finally, in the case of monocycle, the extraction of the pulse train of known shape from the echo is made extremely difficult by the presence of noise of the same frequency. No additional work is recommended.

6.1.2.3 Acoustic Depth Sensor

This sensor suffered from one of the same problems as radar: for the accuracy desired, coal is far too attenuative to allow penetration to any reasonable depth. In addition, ultrasonics requires that the transducer be coupled to the surface whose depth is to be measured. This is, as in the case of the nucleonic sensor, a prohibitive task. No additional work is recommended.

6.1.2.4 Optical Distance Sensor

By use of a well-collimated light source (as from a miner's lamp) illuminating a small area of a surface (e.g., the roof) and focusing lens, it is feasible to measure the distance from the lens to the surface. As the distance shortens, the illuminated spot moves laterally with respect to the principal axis of the lens. Similarly, the image formed by the lens also moves laterally, allowing a calibration between the distance to the surface and the amount the image is translated. Therefore, the amount of image translation can give the distance to the surface.

6.2 Face Alignment Systems

6.2.1 The Angle Cart

As may be concluded from the content of this report, the major emphasis of development was toward control of the shearer's drums, sometimes identified as horizon control. In terms of classical guidance and control terminology, this aspect of the problem is one of pitch control. The remaining control axes are yaw and roll. In this program both yaw and roll were grouped together as the "face alignment system." The basic hardware developed for control in these planes was identified as the "angle cart," which must be tailored to specific longwall machines. The operating principle hinges upon using revolvers to measure the angles formed by adjacent longwall pans; accumulating these measurements in a computer memory; and, knowing the two end points, plotting the trajectory of the track. In practice, skids moved along the Eicotrack, the vertical portion of the pans supporting the rack, which is used in the rack and pinion drive of the Eickhoff shearer. Downface distance was measured by counting the number of revolutions of the drive gear using a ten-digit absolute encoder. The instrument was successfully used in above-ground tests at the Mock Longwall Facility at Bruceton, Pennsylvania, displaying an accuracy of 1 in. in 150 ft. Roll was measured using a pendulous inclinometer made by Moog. Unfortunately, no mine could be found in which to perform the tests after the initial test site was negated by modifications made to the longwall shearer system by the mine operator.

While preliminary testing demonstrated the feasibility of the concept, the machine dependency characteristics of the hardware itself is a deterrent to the "add-on" concept necessary for underground testing. Additionally, relatively few mine operators view face-alignment as significant a problem as horizon control in longwall operations. Full automation, that is, control in all three planes, will ultimately necessitate automatic face control for maximum mining efficiency in use of the longwall system. Thus, it appears that incorporation of a face alignment system should be considered and integrated into the design of an automated longwall shearer.

6.2.2 Optical Alignment

To overcome the problems of machine dependency in face-alignment measuring, a second approach was briefly explored, using hardware designed to prove feasibility

but avoiding those components that would require MSHA approval before in-mine testing [21]. The laboratory model accurately measured face-alignment for 300 ft. The signal was lost when the shearer rounded a bow in the face. Nevertheless, if the design improvements as recommended in Reference 21 are made, an accurate measuring instrument, suitable for commercial use, is feasible.

6.3 Recommendations

At this stage, the horizon control problem is well defined; control algorithms have been defined; and sensors capable of measuring coal depth, determining rock presence, and measuring distances and angles have been developed. In order to bring the system to the point of commercial availability, as well as improve the performance of the system, the following recommendations are made in the following areas:

6.3.1 Control Algorithms

While investigation may turn up better schemes, the present ones are adequate for stable and efficient control. If investigation continues, it should be at a level lower than investigations into other areas. However, computer simulation programs for these control schemes should be kept up-to-date for use in determining the effect of errors, placement of sensors, effect of command rate, etc. (See final report by Foster Miller Assoc., Inc.)

6.3.2 Natural Background Sensor

a) This sensor should be mine-hardened by sealing it and its display from moisture and by shock-isolating some of its more delicate components, e.g., the crystal. Its calibration for a particular mine should be accomplishable at technician level following an explicit algorithm, i.e., "cookbook;" and its field repair should be by means of component replacement by the same type of person.

b) All options have not been exhausted in the placement of the NBS. The deleterious effect of the measurement of coal depth some distance behind the point of cutting has been discussed, as well as some ways of minimizing this effect. It has been suggested that placing the NBS on the cowl would be a way of decreasing this lag and its effects. If one agrees that the equipment could, with adequate protection, survive on the cowl, the next problems encountered are power to the NBS and communication from the NBS.

At the present time, power can be supplied in one of two ways: by means of a battery or by means of power supplied through slip rings. The disadvantage of a battery is that it must be replaced when depleted; the disadvantage of a slip ring is the effort and shearer downtime required to install them. Once installed, they are still subject to damage. If, for these reasons, it is elected to use a battery, then the following is one way in which the NBS could be mounted and used on the cowl.

It is altogether feasible to attach a housing on the cowl, such a housing being large enough to accommodate a crystal of a width and a length somewhat longer than the present one; in other words, a crystal on the order of 2 in. by 12 in. This would be a crystal of 24 in.^{2}. If the counts from bare shale are as few as 5 to 10 counts/sec/in.^{2}, this area will provide a sufficient number of counts for control purposes. The crystal with the photomultiplier tube will account for its longest dimension, which will still be less than the width of the cowl. Within the blister, mount one or more batteries, an NBS processor, and a simple transmitter connected to a primitive antenna flush-mounted on the outside of the blister. The processor is

set so that if the measured coal depth is less than a set lower limit, a single pulse is transmitted to a receiver on the shearer; and if the measured coal depth is greater than an upper limit, then two pulses are transmitted. (One and two pulses are used for illustration. The events could equally well be distinguished by single pulse trains of two different frequencies or by a binary code.) The signal then received could be used on the display for a man-in-the-loop application, or used to actuate the hydraulic valves. This approach naturally assumes that the blister would not interfere with flipping over the cowl.

6.3.3 Sensitized Pick

The sensitized pick has been shown to be capable of distinguishing between rock and coal correctly 70 to 75 percent of the time. The transmission of the strain gage signal by wireless is considered superior to slip rings in terms of installation. The telemetry system requires that the batteries be replaced once a day, or thereabouts. It is recommended that the strain gage signal be processed within the pick block by use of a microprocessor and the processed signal then compared with the criteria for rock and coal (magnitude of a strain, rate of strain, etc.) If the decision is that rock has been struck, a single pulse is transmitted from the drum antenna to the shearer-mounted receiver and action taken accordingly. If the decision is that coal has been struck, no signal is transmitted. Because of the power required to operate a microprocessor; a strain gage; and, occasionally, a resonant circuit powered by a single pulse, battery life ought to be considerably extended. The percent of correct identification may well be improved if the tip of the sensitized pick extends above the height of the standard cutting bits mounted on the drum.

6.3.4 Ionization Detector

When cutting up to roof rock, contact with the rock by the picks is frequently accompanied by the generation of sparks; and the appearance of these sparks is often used by the operator as a guide. It is believed that the onset of sparking could be efficiently detected by a spectrographic means. For example, it appears reasonable to mount such a detector on the chassis and have it viewing, from behind, the cutting of the coal at the roof. The reception of electromagnetic energy at a wave length(s) characteristic of the ionization spectra of the elements involved in the generation of a spark (e.g., calcium, silicon, etc.) would indicate striking the roof. Or, it may be sufficient to detect sparks whose levels are below those that are detectable by the human eye. It is believed that this technique warrants further investigation, because, if successful, it would provide the same information as a sensitized pick, but in a much easier fashion, and would require only a detector mounted on the shearer. While this concept was not tested in the laboratory, it is felt that a deeper investigation is warranted.

BIBLIOGRAPHY

1. Study, Coal Interface Measuring System Final Report, Info Systems, Inc., Waltham, Mass., NAS8-32655.

2. Coal Thickness Gauge Using RRAS Techniques, Southwest Research Institute Final Report, NAS8-32606.

3. Applications of Acoustics in the Measurement of Coal Slab Thickness Final Report, February 26, 1980, Georgia Institute of Technology, NAS8-33093..

4. Design for a Laser Noncontacting Last Cut Follower for Longwall Mine Operations, Science Applications, Inc., December 10, 1979, NAS8-33700.

5. Baseline Studies on the Feasibility of Detecting a Coal/Shale Interface with a Self Powered Sensitized Pick, Wyle Laboratories, February 1, 1981, DEN8-000011.

6. Design for a Mechanical Last Cut Follower Final Report, Mississippi State University, NCA8-00131.

7. Automated Longwall Guidance and Control System Phase I Report, Bendix Corp., September 6, 1978, NAS8-37921.

8. Automated Longwall Guidance and Control System Phase II, Part I (Vertical Control System), Bendix Corp., April 5, 1979, NAS8-32921.

9. Automated Longwall Guidance and Control Phase II, Part II (RCS, FAS and M S), Bendix Corp., June 15, 1979, NAS8-32921.

10. Design of a Laser System for Instantaneous Location of a Longwall Shearer, Adjunct Systems, January 1981, NAS8-34185.

11. The Detection of the Coal Interface by Use of High Pressure Water Final Report, University of Missouri-Rolla, Rolla, Missouri.

12. In-mine Testing of the Sensitized Pick and Vibration Sensor Final Report, Part B, The General Electric Co., NAS8-33064.

13. DOE Contract No. ET-76-C-01-8880, formerly BuMines Contract No. J0166199, Last Cut Survey, A. D. Little, Inc.

14. In-mine Testing of the Natural Background Sensor Final Report, Part A, General Electric Co., NAS8-33064.

15. Vertical Control System Design Review and Baseline Drawings, Foster-Miller Associates, Inc., June 15, 1980, NAS8-33591.

16. Automated Longwall Guidance and Control Vertical Control Subsystem, Final Report Volumes I and II, Foster Miller and Associates, NAS8-33591.

17. Design, Fabrication, and Installation of a Yaw Measuring Device, Benton Corp., June 30, 1979, NAS8-33209.

18. Coal Face Measurement System for Underground Use Final Report, Benton Corp., June 15, 1981, NAS8-33792.

BIBLIOGRAPHY (Continued)

19. Underground Test of Optical Alignment Measuring Instrument, Final Report. Adjunct Systems of Huntsville, Ala., August 28, 1981, NAS8-34185.

20. NASA Technical Memorandum, NASA TM-78208, Transfer Function Tests of the Joy Longwall Shearer.

21. Development of Sensitized Pick Coal Interface Detector System, Shaker Research Corporation, NAS8-32538.

22. Longwall Shearer Guidance and Control, MSSC Final Report TM No. 82455, January 31, 1982.

APPENDIX I

USE OF THE DISPLAY/PROCESSOR AS A DATA LOGGER

The Display/Processor (D/P) was discussed for use as a controller. The D/P contains, in an explosion-proof box, a microcassette recorder (Digital Cassette Drive 82161A), a Hewlitt-Packard 41CV computer, and a microprocessor, and it can accept, process, and analyze the inputs sent to it.*

At the request of the MSHA Birmingham office, a test of the D/P as a data logger was performed at the Jim Walters' No. 5 mine. The test consisted of feeding the output of an MSHA methane sensor, located at the air exhaust of the mine, to the D/P. Because the 41CV is programmable, there are many ways that the sensor output can be treated. The mode selected was to sample the methane sensor output every 30 sec. Upon receipt of the sample, the D/P makes use of the 41CV's mean and standard deviation routine to continuously update the sum of the values and the sum of the squares of the values; furthermore, it does a histogram tally of the successive values as well as determines the peak value. This is done at 30 sec intervals, and, at the hour's end, the D/P loads the values – the mean, the standard deviation, the values for the histogram, and the peak value – onto the tape recorder, and then repeats the same routine for the next hour. The amount of tape required to record the hour's data is so small that many days (approximately 60 days) of data can be recorded. After the accumulation of 6 hr or more of hourly data, the computer goes into a non-parametric statistical routine (counting reverse arrangements) to determine at any desired significance level whether there is a trend in the hourly means.

In the test being described, the D/P was programmed so that it displayed every 30 sec, on the computer display, the present methane percentage level, the trend if six or more consecutive hours were available, and then consecutively displayed the means of the preceding hours of the particular day that it is in. This display is for the operators convenience, and if more information is displayed than he desires, some can be dispensed with. If only the present time and present methane level are displayed, a new sample can be handled every 10 sec rather than every 30 sec.

Analysis of the accumulated data, accumulated possibly over days, can be accomplished using the D/P in conjunction with the Hewlitt-Packard Thermal Printer/Plotter 82162A. The computer can be programmed to receive the recorded data, day by day, on playback, and analyze the data and plot where applicable. The following discussion is concerned with three days data.

Table 1, shows the printout of the data stored on the tape for day 1. The registers, designated by R19 through R167, contain the following information:

---

* Specific designation by name of devices throughout this report is for the purpose of dissemination of information to potential experimenters, and does not constitute an endorsement by the U.S. Government.

R19 – R20	Trend over 24 hr. R19 was inadvertently omitted and should read "DN T" for day 1.
R22	Number of hours.
R24 – R47	Average value for each of the 24 hr, e.g., the mean for the first hour, first day was 0.50124, etc.
R48 – R71	Standard deviation for each of the 24 hr.
R72 – R95	Peak value for each of the 24 hr.
R96 – R119	Number of readings greater than 0.4 and less than 0.5 for each hour.
R120 – R143	Number of readings greater than 0.5 and less than 0.6 for each hour.
R144 – R167	Number of readings greater than 0.6 and less than 0.7.

The information can be taken from the registers and plotted, as shown on Table 2. Table 2 shows the printout of the hourly means and peaks: the graphs are computer plots of these values.

Mention has been made of the trend test. Other tests may be programmed on the computer for a better evaluation of the data: for example, three nonparametric tests (Mann-Whitney, sign, and permutation) were programmed and used to determine if any one day could be considered to be statistically the same as another day (in terms of the hourly means; the peaks could have been used just as well). Using the criterion that if two or more of the three tests agree on significance, it turns out that all three days can be considered to be different (at a 5 percent level of significance for each test). It should be emphasized that once the programs are in the computer, no knowledge of computer programming or statistics is required for the user: the user presses user designated keys, as spelled out by the furnished user instruction sheet, to obtain all printouts of raw data, plots, and statistical analysis.

Because of its mine-permissibility, portability, ruggedness, ease of operation requiring only a simple sheet of "cookbook" instructions and its relatively low cost, it is believed that the D/P will fulfill the requirement for a system that offers much more analytical capability than that potentially available in a strip chart system, without the attendant cost and complexity of a large, stationary computer complex.

TABLE 1. PRINTOUT OF DATA IN REGISTERS FOR DAY 1

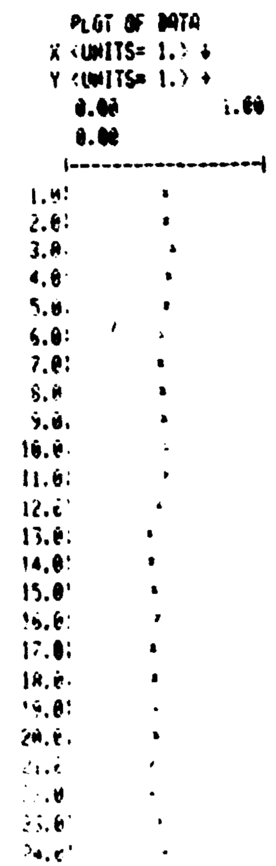
```
DAY1.
MORE DA?

R20= *GEN?
R21= 0.00857
R22= 34.00000
R23= [illegible]
R24= 0.50124
R25= 0.50159
R26= 0.54034
R27= 0.52134
R28= 0.50159
R29= 0.48025
R30= 0.47392
R31= 0.48287
R32= 0.48603
R33= 0.49477
R34= 0.49663
R35= 0.45623
R36= 0.41279
R37= 0.41947
R38= 0.43214
R39= 0.44611
R40= 0.42684
R41= 0.43486
R42= 0.44067
R43= 0.44445
R44= 0.41555
R45= 0.42037
R46= 0.45843
R47= 0.48245
R48= 0.01425
R49= 0.01627
R50= 0.01661
R51= 0.01196
R52= 0.01183
R53= 0.02016
R54= 0.02147
R55= 0.02048
R56= 0.02218
R57= 0.02489
R58= 0.02403
R59= 0.01424
R60= 0.01394
R61= 0.00977
R62= 0.01969
R63= 0.01809
R64= 0.01308
R65= 0.01536
R66= 0.01938
R67= 0.01326
R68= 0.02715
R69= 0.02365
R70= 0.01326
R71= 0.01151
R72= 0.52864
R73= 0.53696
R74= 0.57826
R75= 0.56168
R76= 0.52864
R77= 0.52864
R78= 0.53696
R79= 0.52864
R80= 0.52864
R81= 0.55342
R82= 0.56168
R83= 0.49560
R84= 0.46256
R85= 0.46256
R86= 0.47908
R87= 0.49560
R88= 0.46256
R89= 0.47082
R90= 0.49560
R91= 0.47082
R92= 0.47082
R93= 0.47908
R94= 0.49560
R95= 0.52864
R96= 51.00000
R97= 56.00000
R98= 1.00000
R99= 4.00000
R100= 49.00000
R101= 98.00000
R102= 101.00000
R103= 92.00000
R104= 88.00000
R105= 75.00000
R106= 68.00000
R107= 119.00000
R108= 101.00000
R109= 119.00000
R110= 118.00000
R111= 119.00000
R112= 116.00000
R113= 118.00000
R114= 118.00000
R115= 116.00000
R116= 72.00000
R117= 89.00000
R118= 119.00000
R119= 117.00000
R120= 69.00000
R121= 64.00000
R122= 119.00000
R123= 116.00000
R124= 71.00000
R125= 22.00000
R126= 19.00000
R127= 27.00000
R128= 30.00000
R129= 45.00000
R130= 52.00000
R131= 0.00000
R132= 0.00000
R133= 0.00000
R134= 0.00000
R135= 0.00000
R136= 0.00000
R137= 0.00000
R138= 0.00000
R139= 0.00000
R140= 0.00000
R141= 0.00000
R142= 0.00000
R143= 3.00000
R144= 0.00000
R145= 0.00000
R146= 0.00000
R147= 0.00000
R148= 0.00000
R149= 0.00000
R150= 0.00000
R151= 0.00000
R152= 0.00000
R153= 0.00000
R154= 0.00000
R155= 0.00000
R156= 0.00000
R157= 0.00000
R158= 0.00000
R159= 0.00000
R160= 0.00000
R161= 0.00000
R162= 0.00000
R163= 0.00000
R164= 0.00000
R165= 0.00000
R166= 0.00000
R167= 0.00000
PLOT? R/S
```

TABLE 2. PRINTOUT AND PLOT OF MEAN FOR EACH DAY
X=HOURS, Y=PERCENT METHANE (1% FULL SCALE)

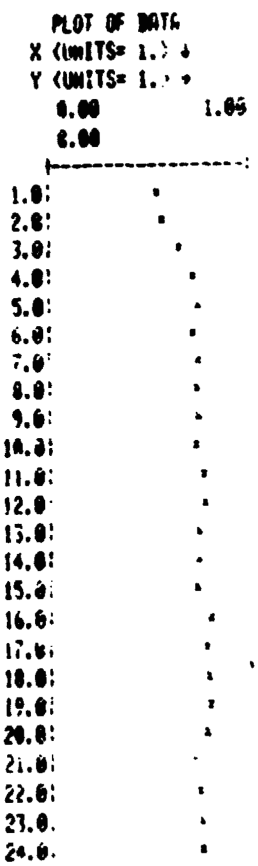
DAY1.

NODE	MEAN
R24=	0.50124
R25=	0.50159
R26=	0.54034
R27=	0.52134
R28=	0.50159
R29=	0.46025
R30=	0.47392
R31=	0.40287
R32=	0.40683
R33=	0.45477
R34=	0.49663
R35=	0.45623
R36=	0.41275
R37=	0.41947
R38=	0.43214
R39=	0.44611
R40=	0.42604
R41=	0.43406
R42=	0.44067
R43=	0.444
R44=	0.415[illegible]
R45=	0.42037
R46=	0.45643
R47=	0.40245



DAY2.

NODE	MEAN
R48=	0.55328
R49=	0.57552
R50=	0.65867
R51=	0.72798
R52=	0.75304
R53=	0.72505
R54=	0.74973
R55=	0.74278
R56=	0.75656
R57=	0.73562
R58=	0.77754
R59=	0.78532
R60=	0.75441
R61=	0.75606
R62=	0.74676
R63=	0.80742
R64=	0.78766
R65=	0.79764
R66=	0.80253
R67=	0.79305
R68=	0.72963
R69=	0.75042
R70=	0.75905
R71=	0.76291



DAY3.

NODE	MEAN
R72=	0.77479
R73=	0.76095
R74=	0.74966
R75=	0.71683
R76=	0.68647
R77=	0.70382
R78=	0.75930
R79=	0.75400
R80=	0.72904
R81=	0.73672
R82=	0.72674
R83=	0.66961
R84=	0.54723
R85=	0.55817
R86=	0.59272
R87=	0.58605
R88=	0.60443
R89=	0.59706
R90=	0.57634
R91=	0.56065
R92=	0.53091
R93=	0.52176
R94=	0.53174
R95=	0.57345

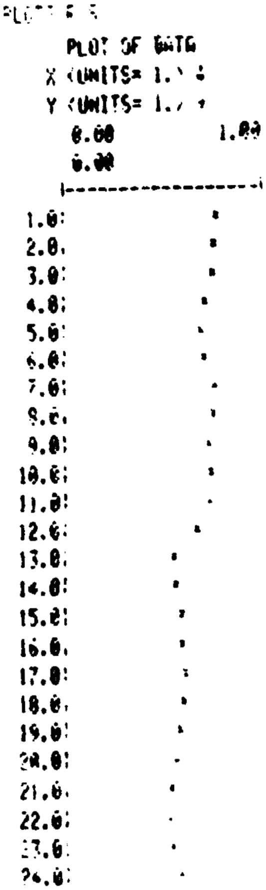
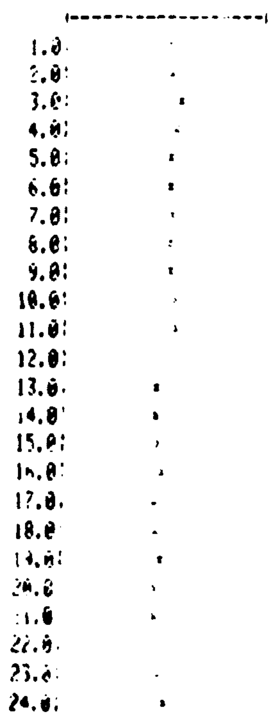


TABLE 2. (Concluded)

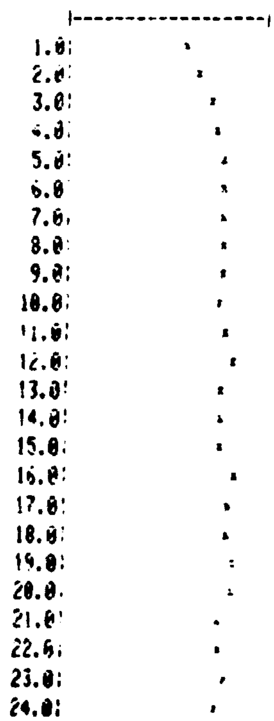
DAY1. MODE PEAK		DAY2. MODE PEAK		DAY3. MODE PEAK	
R24=	0.52864	R48=	0.59472	R72=	0.80946
R25=	0.53690	R49=	0.66080	R73=	0.70476
R26=	0.57620	R50=	0.72688	R74=	0.79296
R27=	0.56168	R51=	0.75992	R75=	0.74340
R28=	0.52864	R52=	0.79296	R76=	0.72688
R29=	0.52864	R53=	0.79296	R77=	0.80122
R30=	0.53690	R54=	0.79296	R78=	0.80948
R31=	0.52864	R55=	0.79296	R79=	0.80302
R32=	0.52864	R56=	0.79296	R80=	0.79296
R33=	0.55342	R57=	0.77644	R81=	0.79296
R34=	0.56168	R58=	0.80948	R82=	0.80122
R35=	0.49560	R59=	0.84252	R83=	0.74340
R36=	0.46256	R60=	0.79296	R84=	0.62776
R37=	0.46256	R61=	0.79296	R85=	0.59472
R38=	0.47908	R62=	0.79296	R86=	0.66080
R39=	0.49560	R63=	0.85904	R87=	0.62776
R40=	0.46256	R64=	0.82600	R88=	0.64428
R41=	0.47082	R65=	0.82600	R89=	0.62776
R42=	0.49560	R66=	0.85904	R90=	0.60298
R43=	0.47082	R67=	0.85904	R91=	0.59472
R44=	0.47082	R68=	0.79296	R92=	0.56168
R45=	0.47908	R69=	0.90122	R93=	0.56166
R46=	0.49560	R70=	0.82600	R94=	0.65254
R47=	0.52864	R71=	0.79296	R95=	0.66080

PLOT? R/S

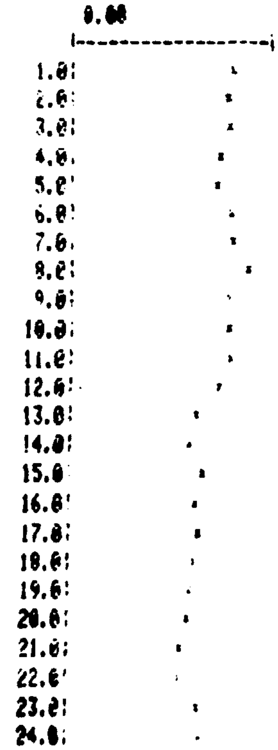
PLOT OF DATA
X (UNITS= 1.) ↓
Y (UNITS= 1.) →
0.00 1.00
0.00



PLOT OF DATA
X (UNITS= 1.) ↓
Y (UNITS= 1.) →
0.00 1.00
0.00



PLOT OF DATA
X (UNITS= 1.) ↓
Y (UNITS= 1.) →
0.00 1.00
0.00



APPROVAL

LONGWALL SHEARER GUIDANCE AND CONTROL

FINAL REPORT

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

Jack C. Swearingen

Jack C. Swearingen, Manager
Special Projects Office

U.S. GOVERNMENT PRINTING OFFICE 1982—546-071/145 REGION NO. 4